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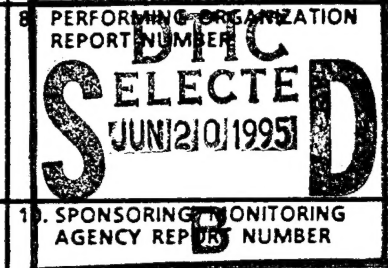
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13. ABSTRACT (Maximum 200 words)

Since October, 1986, the Center for Advanced Materials of High Quality Dynamic Performance has been established at the University of California, San Diego, by the Army Research Office, Durham, as part of DoD's University Research Initiative. This phase of this URI continued to June, 1992 (including a no-cost extension). This multidisciplinary Center focused on a coordinated macroscopic and microscopic experimental and theoretical characterization and constitutive modeling of the mechanical response and the failure modes of advanced materials at ultrahigh strain rates.

The Center has developed unique state-of-the-art instrumentation for controlled mechanical testing of metals, metal-matrix composites, ceramics, and ceramic composites, over the full range of strain rates from quasi-static to greater than  $10^6/s$ , and temperatures from  $-200^\circ C$  to greater than  $1000^\circ C$ , with complete time-resolved data acquisition systems. Among the Center's major contributions are novel dynamic recovery techniques invented for split Hopkinson bars, normal and oblique plate impact experiments, and laser-induced compression/tension involving pulses of extremely short duration and high amplitude. These are expected to impact the nature of future high strain rate testing. This is paralleled by physically-based micromechanical models of high strain, high strain rate plastic flow of metals, microcracking, phase transformation, and damage evolution in advanced ceramics and their composites. A breakthrough has been made in computational algorithms, which provides a powerful tool for constitutive computational modeling of the nonlinear response and failure modes of ductile materials. These activities have been accompanied by strong graduate training involving MS, Ph.D., and post-doctoral ingredients; by short courses, a new Materials Science Graduate Program, several workshops and symposia; and by close collaborative research with scientists from the Army's MTL and BRL, and several DoE laboratories.

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**Center for Advanced Materials of High Quality  
Dynamic Performance  
(Center of Excellence) (Research)**

**FINAL TECHNICAL REPORT**

**Principal Investigator: Dr. S. Nemat-Nasser**

**for the period  
October 1, 1986 - June 30, 1992  
(includes no-cost extension)**

**U.S. Army Research Office  
ARO Proposal Number: 24617-MS-UIR  
Grant No.: DAAL03-86-K-0169**

**University of California, San Diego**

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**CENTER FOR ADVANCED MATERIALS OF HIGH QUALITY  
DYNAMIC PERFORMANCE  
(CENTER OF EXCELLENCE)\***

**1. INTRODUCTION**

Since October, 1986, the Center for Advanced Materials of High Quality Dynamic Performance (Center of Excellence) has been established at the University of California, San Diego, by the Army Research Office, Durham, as a part of DoD's University Research Initiative. This phase of this URI continued to June, 1992 (including a no-cost extension). This multidisciplinary Center focused on a coordinated macroscopic and microscopic experimental and theoretical characterization and constitutive modeling of the mechanical response and the failure modes of advanced materials at ultrahigh strain rates.

The presence of the Center accelerated the University's efforts to develop a program of studies and advanced research in materials science. It also provided a focal point through which the University, national and Army laboratories, and industry have worked together toward common scientific and technological goals, i.e., to understand and, hence, control the failure modes of advanced materials in severe environments. Close collaboration among graduate students, postdoctoral fellows, visiting scholars, and faculty members active in the Center, and scientists from national and Army laboratories and industry has been cultivated through direct participation by representatives from these laboratories and industry in the Center, and through participation in seminars, workshops, and conference meetings coordinated at the Center.

The Center has developed unique state-of-the-art instrumentation for controlled mechanical testing of metals, metal-matrix composites, ceramics, and ceramic composites, over the full range of strain rates for quasi-static to greater than  $10^6/s$ , and temperatures from  $-200^\circ\text{C}$  to greater than  $1000^\circ\text{C}$ , with complete time-resolved data acquisition systems. Among the Center's major contributions are novel dynamic recovery techniques invented for split Hopkinson bars, normal and oblique plate impact experiments, and laser-induced compression/tension involving pulses of extremely short duration and high amplitude. These are expected to impact the nature of future high strain rate testing. This is paralleled by physically-based micromechanical models of high strain, high strain rate plastic flow of metals, microcracking, phase transformation, and damage evolution in advanced ceramics and their composites. A breakthrough has been made in computational algorithms, which provides a powerful tool for constitutive computational modeling of the nonlinear response and failure modes of ductile materials.

This final technical report summarizes the Center's scientific, instructional, and related achievements.

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\* This URI was initiated under the name 'Center of Excellence for Ultradynamic Performance Materials' and later the name was changed by the review panel to 'Center for Advanced Materials of High Quality Dynamic Performance (Center of Excellence)'. Since then, this Center has been referred to by both names.

## 2. OBJECTIVES AND ORGANIZATION

### 2.1. Aims and Research Components of the Center

The prediction by analytical, computational, and experimental techniques of the response of advanced materials (such as refractory metals, ceramics, and advanced composites) to dynamic loads applied at ultrahigh rates, has been a fundamental issue of considerable importance to DoD and industry. While good progress has been made in recent years in synthesizing materials of high-quality static performance, the problem of predicting, and hence controlling, their dynamic performance has remained a challenge worthy of serious and continuing commitment of time and resources in a coordinated, multidisciplinary manner. The problem involves: microstructural characterization of advanced materials through electron microscopy and other advanced techniques; macroscopic material characterization through macroscopic material testing under general three-dimensional stress conditions in controlled environments; micromechanically based analytic material modeling to develop constitutive relations for inelastic response and failure modes; implementation of these constitutive relations into large-scale advanced computer programs; and finally, dynamic experiments with Hopkinson bars, high-speed flyer plates or intense laser beams and the associated experimental diagnostics which, at the envisioned rates, have required development beyond the state-of-the-art that existed at the beginning of this URI. This challenge was met through a multidisciplinary, carefully integrated program of materials engineering, solid mechanics, applied mathematics, large-scale computational mechanics, and experimental shock physics. The multidisciplinary Center for Advanced Materials of High Quality Dynamic Performance (Center of Excellence) at the University of California, San Diego, provided a unique environment for research and graduate education on advanced materials of high-quality performance under the ultrahigh rates of loading associated with impact and intense energy impingement.

Aims of the Center:

- Through coordinated experimental, theoretical, and computational methods, to develop the scientific and technological know-how for analysis and design of advanced materials with tailored microstructures which will have desired macroscopic properties under ultrahigh rates of straining.
- To provide a high-quality intellectual atmosphere for doctoral and postdoctoral advanced education in an integrated materials engineering program with strong input from materials science, mechanics and applied mathematics, computational mechanics, and shock physics.
- To provide a forum for scientific exchange and research and collaborative work among advanced students and scientists selected from various universities, UC-National Laboratories, Army laboratories, and industry.

### 2.2. Major Research Components

The Center focused on three major and interrelated scientific areas (see Figs. 1 and 2):

- Materials

This included microstructural characterization of undamaged and damaged materials, examination of the effects of metallurgical variables on the mechanical response, macromechanical characterization through quasi-static experiments at various temperatures in controlled environments, and any necessary materials development.

- Modeling and Computation

This included micromechanical modeling of nonlinear response and failure modes, constitutive characterization of materials at high and ultrahigh strain rates, the associated computer algorithms to be used in large-scale computer programs, and numerical experimentation and computer prediction of

material behavior under ultrahigh strain rates.

- Dynamic Tests

This included high and ultrahigh strain-rate *recovery* experiments on specific advanced materials with controlled microstructures, using Hopkinson bars, flyer plate, and high-energy laser facilities. This has resulted in new developments in dynamic testing techniques and time-resolved diagnostics of high strain-rate experiments through high-speed flash photography, X-ray photography, and innovative holography. Some of the novel facilities that now exist at UCSD have not yet been copied elsewhere.

Figures 1 and 2 show schematically the major research components of the Center and their interrelation. Micromechanical modeling, development of constitutive relations, and failure analysis were guided by input from the analysis of the materials' microstructures, as well as from macromechanical material characterization by quasi-static tests. The results of such a microscopically based analysis were the basis of developing phenomenological constitutive equations to be used in large-scale computer programs. Since dynamic recovery tests at high strain rates were extremely complex and expensive, they had to be carefully planned, with extensive diagnostics, in order to obtain the maximum possible information. The design of such dynamic tests, therefore, were guided by microscopic material observations, extensive quasi-static tests, and analytical and computational studies. In turn, data obtained from dynamic tests provided an important and vital basis for the assessment of material response and the evolution of damage, and, therefore, guided further research in constitutive modeling and failure analysis.

The result of such integrated and carefully coordinated research was a more in-depth understanding of the effects of microstructural and metallurgical variables on the macroscopic response and failure modes of advanced materials subjected to high and ultrahigh strain-rate loadings. This would lend to a better and scientifically based design of material microstructure for desired quality dynamic performance. The driving objective for the Center has been:

to design advanced materials with desired tailored microstructures for quality performance under ultrahigh load-rates, and to *predict* their dynamic response by microscopic observation and macromechanical experiments, and theoretical modeling and computational methods.

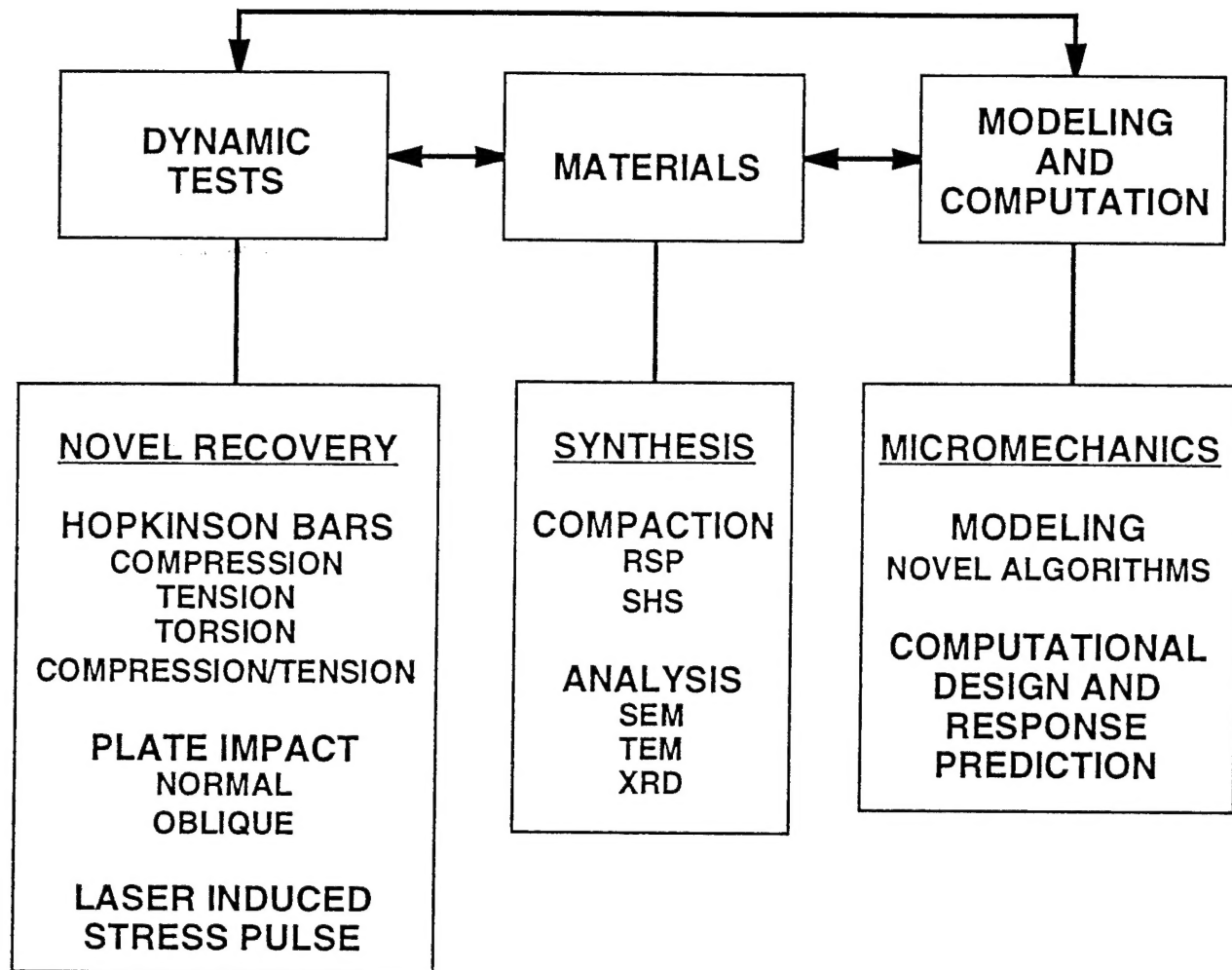


Figure 1: Major Research Components of the Center and Their Interrelation

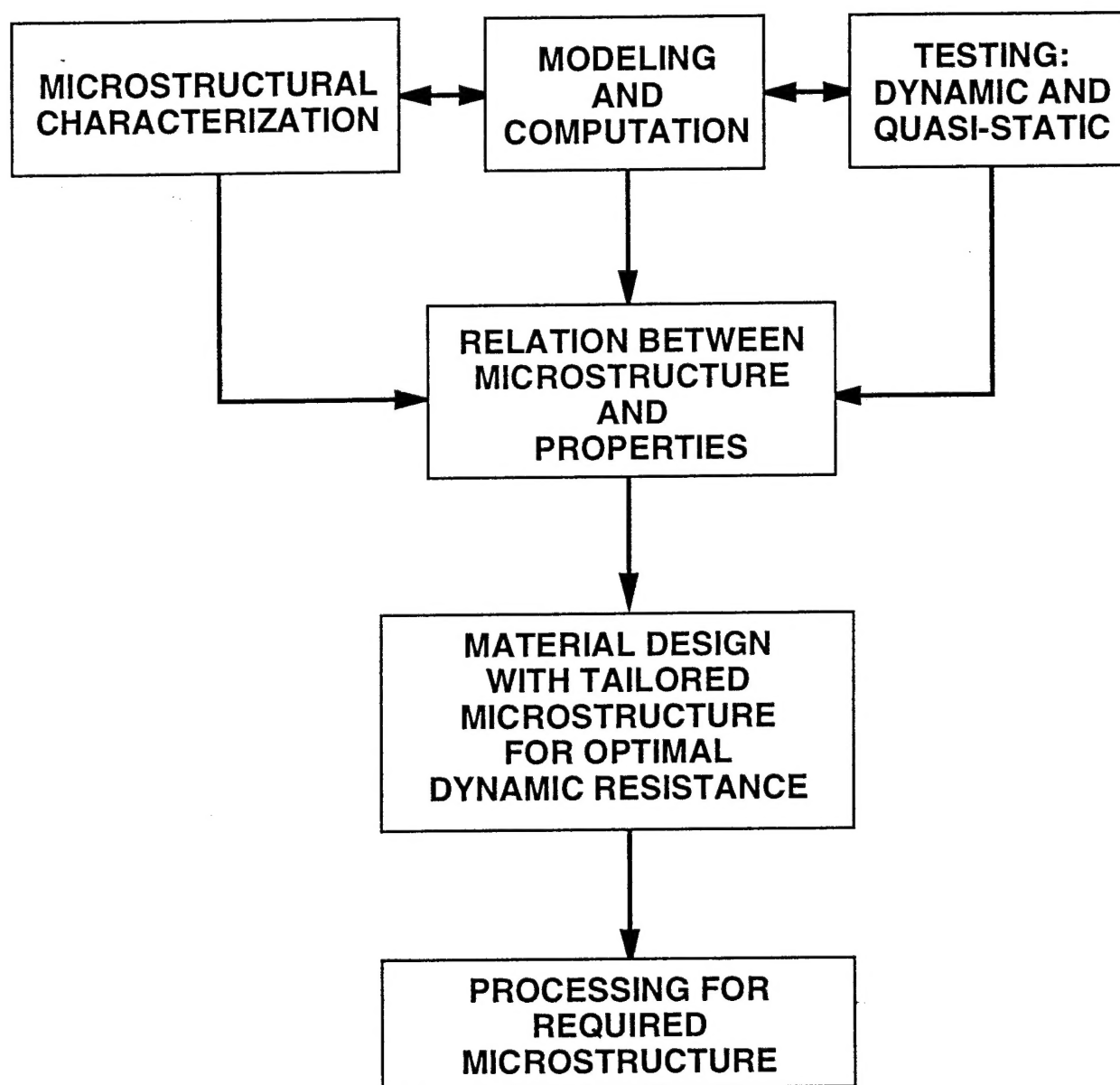


Figure 2: Advanced Materials' Design: A Coordinated Experimental and Theoretical Program

### 2.3. Management

The Center was coordinated by a Director and an Administrative Committee of three UCSD faculty members, a principal development engineer, a development engineer, and an executive secretary. Table 1 lists the members of the Administrative Committee. This committee met regularly, often two or three times a week, in order to handle all of the affairs of the Center, including teaching, research, and other activities.

**TABLE 1**  
ADMINISTRATIVE COMMITTEE

- |                             |                                 |
|-----------------------------|---------------------------------|
| • G. Hegemier               | • M. Meyers, Associate Director |
| • S. Nemat-Nasser, Director | • J. Starrett (deceased 5/90)   |
| • J. Isaacs                 | • D. Lischer                    |
| • L. Jacobs-Cohantz         |                                 |

The overall activities of this URI Center were reviewed and directed by an Executive Committee, chaired by the Director. This committee included one representative scientist from ARO or Army laboratories, one member of UCSD, and one rotating member from a participating UC campus or national laboratory other than UCSD. The members of this committee are listed in Table 2. The committee met twice a year in order to review in a broad sense the program of the Center and its plans.

**TABLE 2**  
EXECUTIVE COMMITTEE

- |                              |                                 |
|------------------------------|---------------------------------|
| • K. Iyer, <i>ex officio</i> | • A. Crowson, <i>ex officio</i> |
| • G. Hegemier                | • M. Meyers, Vice Chair         |
| • S. Nemat-Nasser, Chair     |                                 |

ARO had a review panel which formally reviewed the Center's activities at least once a year; informally, the Center was reviewed periodically by various panel members and ARO, DoD, and DARPA officials. Table 3 lists the official members and the review panel's invitees.

**TABLE 3**  
OFFICIAL REVIEW PANEL

- |               |               |
|---------------|---------------|
| • G. Anderson | • M. Azrin    |
| • G. Bishop   | • W. Bruchey  |
| • R. Chait    | • T. Chou     |
| • J. Clark    | • W. Ebihara  |
| • J. Frasier  | • K. Iyer     |
| • G. Mayer    | • T. Nicholas |
| • J. Walter   |               |

### 3. PERSONNEL

#### 3.1. Core Contributors

- S. Nemat-Nasser, Director of the Center of Excellence for Advanced Materials, micromechanics, constitutive modeling, and fracture
- D. Benson, computational solid mechanics
- A. Chokshi, superplasticity, ceramic composites
- G. Hegemier, composite materials, structural mechanics
- M. Meyers, Associate Director, shock consolidation, phase transformation
- H. Murakami, composite materials, computational mechanics
- K. Vecchio, analytical electron-microscopy, fatigue and fracture
- A. Ellis, experimental mechanics, cavitation (deceased 4/91)
- M. Simnad, materials and nuclear engineering

#### 3.2. Associated Faculty Members

- J. Kosmatka, composite materials and structures
- X. Markenscoff, elastodynamics, dislocation theory
- J. McKittrick, ceramic materials, synthesis, characterization

#### 3.3. Technical Support

- J. Haugdahl, Principal Electronic Technician (part-time)
- J. Isaacs, Development Engineer
- D. Lischer, Development Engineer
- J. Starrett, Principal Development Engineer (deceased 5/90)

#### 3.4. Fellows (Graduate Students) - *see Table 4*

#### 3.5. Graduate Research Assistants (Full or Partial Support) - *see Table 4*

#### 3.6. Undergraduate Assistants

- Y. Chen (M.A. Meyers, advisor, 7/93-9/93)
- B. Ellman (S. Nemat-Nasser, advisor, 9/88-6/90)
- N. Immaneni (M.A. Meyers, advisor, 6/91-4/93)
- E. Miley (S. Nemat-Nasser, advisor, 10/91-6/92)
- R. Oneto (S. Nemat-Nasser, advisor, 9/92-6/92)
- N. Tang (S. Nemat-Nasser, advisor, 10/90-6/91)
- L.-H. Yu (M.A. Meyers, advisor, 10/92-4/93)

### 3.7. Postdoctoral Research Engineers (Full or Partially Support) - see Table 4

#### *Description of Research:*

- M. Ahmadshahi, Moire interferometry and dynamic holography
- S. Chang, phase transformation, high strain rate deformation, dynamic compaction, mechanical metallurgy, and electron-microscopy
- D.-T. Chung, dynamic behavior of PSZ under uniaxial strain conditions
- M. Hori, micromechanical modeling and analysis of crystalline solids; failure mechanism of fiber-reinforced composites
- S. Krishnaswamy, dynamic holography and material testing
- Y. Mikata, micromechanical modeling of dynamic response of ceramics and ceramic composites and wave propagation in elastic composites
- L. Ni, dynamic interface cracks (partially supported)
- A. Nohara, evolution of microstructure using transmission electron-microscopy
- K.T. Ramesh, mechanics of solids and structures; precision engineering and instrumentation
- M. Rashid, theoretical, experimental, and numerical characterization of inelastic processes in materials
- W. Rogers, damage evolution laser induced stress-pulse technique

### 3.8. Degrees Awarded for Work Completed (Full or Partially Supported)

#### I. Ph.D. Degrees

- B.S. Altman (1992) Thesis: Dynamic Deformation and Analysis of Metal Matrix Composite
- H. Deng (1993) Thesis: Dynamic Damage Evolution in and Failure of Brittle Solids in Compression (partially supported)
- S. Ghatuparthi (1991) Thesis: Dynamic Behavior of Zirconia Ceramics in Uniaxial Compression (partially supported)
- M. Hori (1987) Thesis: Void Collapse and Void Growth in Crystalline Solids
- J. LaSalvia (1994) Thesis: An Investigation into the Synthesis and Processing of Dense Titanium Carbide-Nickel-Molybdenum Based Cermets Utilizing Combustion Synthesis with Impact Forging (partially supported)
- Y.-F. Li (1993) Thesis: Constitutive Algorithm, Constitutive Modeling and Simulation of High-Strain, High-Strain-Rate Finite-Deformation of Heavy Metals (partially supported)
- A. Machcha (1994) Thesis: Dynamic Response of Materials at High Loading Rates: A Study on Ceramics and EDH Lubricants (partially supported)
- D. Owen (1994) Thesis: An Investigation into the Free Sintering and Sinter Forging Behavior of Single and Dual Phase Alumina-Zirconia Ceramics (partially supported)
- M. Rashid (1990) Thesis: High-Strain-Rate Plastic Flow in Metallic Single Crystal
- V. Sharma (1994) Thesis: Damage Evolution in Hot-Pressed Silicon-Nitride Under Repeated Dynamic and Quasi-Static Compression Loading (partially supported)
- A. Thakur (1994) Thesis: Deformation Behavior and Bauschinger Effect in Super Alloy (partially supported)

- N. Yu (1992) Thesis: Overall Properties of Composite Materials: A General Model Based on Periodic Microstructure (partially supported)
- M. Zikry (1990) Thesis: High-Strain-Rate Deformation and Failure of Crystalline Materials

## II. M.S. Degrees

- B.S. Altman (1989) Project: Normal Plate Impact Recovery Experiments on  $B_4C/Al$  Cermet
- S. Ghatuparthi (1989) Thesis: Experimental Investigation of Fabric-Stress Relations in Granular Materials
- T. Mizuno (1989) Project: Fatigue and Tensile Tests of Single and Polycrystalline Copper
- J.M. Schwartz (1989) Thesis: Compression-Induced Void Collapse and Brittle Fracture in Iron and Steel
- A. Machcha (1990) Comprehensive Examination
- Y. Sano (1990) Thesis: Nucleation and Growth of Martensite Induced by a Tensile Stress Pulse in Fe-31.8 WT % Ni-0.020 WT % C Alloy

### 3.9. Placement of Associates - *see Table 4*

### 3.10. Visiting Scientists

The Center sought to promote scientific exchange and collaborative work with key scientists throughout the country who were working in areas of special interest to the Center. This was done by inviting scientists to visit the Center for periods of a few days up to possibly one year, collaborating with scientists at the Center and supervising students' work. In addition, the Center strongly promoted collaborative work with industry and government laboratories, especially with Army laboratories.

#### 3.10.1. Visitors from Army Laboratories

The following visitors from Army Laboratories participated in the Center's activities:

- Dr. Michael R. Staker, Processing Technology Division, Army Materials Technology Laboratory, Watertown, Massachusetts, June 3, 1987 to September 1, 1987, collaboration on shear band analysis
- Dr. Thomas W. Wright, U.S. Ballistic Research Laboratory, Aberdeen Proving Grounds, Maryland, June 29, 1987 to July 31, 1987
- Dr. Dennis Viechnicki, Ceramics Research Branch, Army Materials Technology Laboratory, May 9, 1989
- Dr. Robert O'Donnell, MRL, Australia, while visiting MTL, Watertown, Massachusetts, May 5, 1989
- Dr. Andrew Nüler, U.S. Ballistic Research Laboratory, Aberdeen Proving Grounds, Maryland, August 1 to August 28, 1989, collaboration on synthesis and dynamic testing of titanium carbide
- Dr. Thomas W. Wright, U.S. Ballistic Research Laboratory, Aberdeen Proving Grounds, Maryland, January 9, - February 2, 1990

Table 4: Education: Training of Future Scientists

**URI Fellows**

M. Zikry (Ph.D. July 90)  
 M. Rashid (Ph.D. June 90)  
 B. Altman (Ph.D. June 92)  
 D. Owens (Ph.D. December 93)  
 J. LaSalvia (Ph.D. June 94)  
 R. Crafts (M.S. September 92)  
 T. Winter (M.S. June 91)

**Current Position**

Assistant Professor, North Carolina State University  
 Assistant Professor, University of California, Davis  
 Staff Researcher, Sandia National Laboratories  
 Post-Doctoral Researcher, California Institute of Technology  
 Post-Doctoral Researcher, IMM, UCSD

**Graduate Research Assistants  
with Full or Partial Support**

B. Forner (M.S. June 90)  
 S. Ghatuparthi (Ph.D. November 91)  
 N-I. Yu (Ph.D. December 92)  
 H. Deng (Ph.D. February 93)  
 Y-F. Li (Ph.D. August 93)  
 A. Machcha (M.S. August 90  
                   Ph.D. August 94)  
 A. Thakur (Ph.D. October 94)  
 Y. Sharma (Ph.D. September 94)  
 T. Mizuno (M.S. March 89)  
 J.M. Schwartz (M.S. January 89)  
 Y. Sano (M.S. August 90)

**Current Position**

Boeing Company  
 Assistant Professor, Michigan Technological University  
 Assistant Professor, University of Tennessee  
 Post-Doctoral Researcher, University of California, Los Angeles  
 Research Scientist in Taipei Taiwan  
 Post-Doctoral Researcher, University of California, San Diego  
  
 Post-Doctoral Researcher, University of California, San Diego  
 Post-Doctoral Researcher, University of California, San Diego  
  
 GIS Technician, Las Vegas Water District  
 Chief Engineer, Sumiden Wire Products Corporation, Tennessee

**Post-Doctoral Research Engineers    Current Position**

M. Ahmadshahi (July 89 to April 92)	Senior Engineer, CE Niehoff & Co., Illinois
W. Rogers (October 87 to August 89)	Associate Professor, University of Colorado
S. Krishnaswamy (Nov 89 to October 90)	Assistant Professor, Northwestern University
Y. Mikata (August 87 to August 90)	Assistant Professor, Old Dominion University
K.T. Ramesh (November 87 to August 88)	Assistant Professor, The Johns Hopkins University
M. Rashid (August 90 to January 92)	Assistant Professor, University of California, Davis
S-N. Chang (April 87 to September 90)	Senior Researcher, Agency of Defense Development, Korea
D-T. Chung (September 86 to December 89)	Senior Researcher, Agency of Defense Development, Korea
A. Nohara (July 88 to May 90)	Associate Professor, Nagoya University, Japan
M. Hori (September 87 to September 89)	Assistant Professor, University of Tokyo, Japan
L. Ni (August 90 to June 92)	Research Engineer, University of California, San Diego

- Lt. John H. Beatty, U.S. Army Material Technology Laboratory, Watertown, Massachusetts, March 10 - May 11, 1990, collaboration on dynamic testing and shear bands in steels
- Dr. Steve Segletes, U.S. Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, October 27, 1990 - November 4, 1990, collaboration on flow of granular materials
- Dr. Marty Raftenberg, U.S. Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, 1991, collaboration on computational viscoplasticity and hole growth in metals

### 3.10.2. Visitors from National Laboratories

- Dr. Paul S. Follansbee, Los Alamos National Laboratory, Los Alamos, New Mexico, March 21, 1988 to June 3, 1988, and January 10 and 11, 1989, collaboration on Hopkinson bar experiments on iron
- Dr. William O. Nellis, Lawrence Livermore National Laboratory, Livermore, California, April 3, 1989 to June 9, 1989, collaboration on gas gun design and shock processing
- Dr. Keith Wilfinger, Lawrence Livermore National Laboratory, January, 1988 and October, 1989
- Lieutenant John Bridge, USAF, Lawrence Livermore National Laboratory, January, 1988
- Dr. Wayne King, Lawrence Livermore National Laboratory, May, 1989
- Dr. Anna Zurek, Los Alamos National Laboratory, June 21, 1989
- Dr. Lee Tanner, Lawrence Livermore National Laboratory, December 19, 1988
- Mr. Charles Frantz, Los Alamos National Laboratory, March 1988
- Dr. Zafar Iqbal, Allied Technologies, April 26, 1989
- Dr. George T. Gray, Lawrence Livermore National Laboratory, April 2 - June 22, 1990, collaboration on dynamic testing and characterization of metals and ceramics

### 3.10.3. Collaboration with Scientists from DoE, DoD, and Other Institutions

- Lawrence Livermore National Laboratory: Mr. Danny Halverson, Dr. Richard Landingham, and their co-workers; B<sub>4</sub>C/Al
- Tulane University: Professor M.M. Mehrabadi; Flow of Granular Materials (collaboration with S. Nemat-Nasser and G. Subhash)
- Stanford University: Professors George Herrmann, Thomas J.R. Hughes, and Juan C. Simo; Micromechanics and Modeling of Damage, Large-Scale Computations (collaboration with S. Nemat-Nasser, R.J. Asaro, and G.A. Hegemier)
- Brown University: Professors Joseph Kestin; Thermodynamic Foundation of Damage Modeling (collaboration with S. Nemat-Nasser)
- The Johns Hopkins University: Professor K.T. Ramesh; Plate Impact Experiments of B<sub>4</sub>C/Al Cermets (former postdoctoral fellow of our Center, collaboration with S. Nemat-Nasser, G. Ravichandran, and Brad Altman)
- California Institute of Technology: Professor Ares Rosakis; Dynamic Fracture Experiments and Computational Analysis (collaboration with G. Ravichandran)
- Lawrence Livermore National Laboratory: Dr. Lee Tanner, Phase Transformation (collaboration with Marc Meyers, S. Nemat-Nasser, Soon-Nam Chang)
- University of Bath: Professor John Willis; Asymptotic Methods; Micromechanics (collaboration with S. Nemat-Nasser).
- Sandia National Laboratory: Dr. Lee Taylor; Large Scale Computations (collaboration with S. Nemat-Nasser and D.-T. Chung).

- Los Alamos National Laboratories: Dr. W. Blumenthal; Testing of  $B_4C/Al$  Cermets in Compression Hopkinson bar (collaboration with G. Ravichandran and J. Isaacs)
- Sandia National Laboratory: Dr. Dennis Grady; Shock Response of Ceramics (collaboration with S. Nemat-Nasser and M. Meyers)
- University of Bath: Professor John Willis; Asymptotic Techniques for Strongly Singular Integral Equations with Application to Crack Bridging
- Tohoku University: Professor Muneo Hori; co-authoring a book on "Micromechanics: Overall Properties of Heterogeneous Elastic Solids" with S. Nemat-Nasser, Crack Bridging, Damage in Ceramics by Microcracking
- Fraunhofer-Institute für Angewandte Materialforschung: Dr. Lothar W. Meyer; Adiabatic Shear Banding, Self-Propagating, High Temperature Synthesis (collaboration with M.A. Meyers and S. Nemat-Nasser)
- Ames Laboratory: Professor Arthur K. Gautesen; Singular Integral Equations and Asymptotic Method, Interface Cracks
- University of Michigan: Professor John E. Taylor; Mechanics of Solids and Optimization
- Nagoya Institute of Technology: Professor Norio Hasebe; Fracture Mechanics
- Northwestern University: Professor W.E. Olmstead; Singular Integral Equations and Asymptotic Methods, Adiabatic Shear Banding
- Tulane University: Professor Morteza Mehrabadi; Mechanics of Granular Materials
- University of East Anglia: Dr. Leslie Morland; Nonlinear Waves in Solids, Constitutive Relations

#### 3.10.4. Collaboration with Industry

- Contact was established with Dr. Rich Pallicka of CERCOM in Vista, California, who makes advanced ceramics and ceramic composites. In our technical discussions, he recommended that silicon nitride is an excellent model material and the microstructure can be tailored. A strong technical collaboration with CERCOM in obtaining and characterizing materials was established. Drs. Pallicka and Ezis were invited to visit our facilities and discuss collaboration.
- Drs. Alec Pyzik and Arie Cohen of Dow Chemical's Central Research, Midland, Michigan visited our high strain rate testing facilities and we had a discussion with them on the processing and testing of ceramic composite materials. Dr. Pyzik presented a technical seminar on the processing of boron carbide-aluminum composites.
- Drs. Jeff Wardsworth and T. G. Nieh of the Lockheed Missile Company, Palo Alto, California visited our facilities and discussed the possibility of testing certain materials such as copper and tungsten in our tension split Hopkinson bar.
- Professor S. Nemat-Nasser, D.-T. Chung, and M. Rashid have been collaborating with Drs. Y. R. Rashid and Robert Dunham of Anatech International, La Jolla, California, over the past three years on computational modeling of high strain rate elastoplastic deformation of crystalline metals, using both phenomenological and micromechanical constitutive models.
- The Center has ongoing collaboration with Trans-Science in La Jolla, California. The work involves micromechanical modeling of damage and fragmentation of ceramics and composites under high loading rates.
- Close collaborative work with several scientists at GA Technologies was initiated from the inception of the Center at UCSD. This involved both instructional and research collaboration. The scientists from GA Technologies included Drs. Terry Gulden, James Kaae, and C.-Y. Hsu. The Center's leading participants were: S. Nemat-Nasser, M.A. Meyers, G.

Ravichandran, and G. Hegemier.

- Drs. Keith Kedward and Henry Paris of McDonnell Douglas Technologies, Inc. (formerly known as ALCOA Defense Systems), San Diego, California, have continued to collaborate with M. Simnad, S. Nemat-Nasser, and G. Ravichandran on dynamic deformation and micromechanical characterization of nicalon-aluminum phosphide. Dr. Henry Paris has also assisted S. Nemat-Nasser in teaching a graduate course in Materials at UCSD.
- Drs. David Schuster and Michael Skibo of Dural Industries, San Diego, California, have been collaborating with S. Nemat-Nasser, J. Starrett, J. Schwartz, and B. Altman on establishing the mechanical behavior of SiC/Al.
- Several scientists from SAIC have had contact with the Center's scientists over the past three years. SAIC has donated scientific instruments to the Center.
- Dr. Sabodh K. Garg of S-Cubed and S. Nemat-Nasser and G. Hegemier, and Dr. M. Hori have been collaborating on micromechanical modeling of dynamic void collapse and void growth in crystalline solids. Several papers have emerged as a result of this collaboration.
- Dr. Santosh Arya of TRW and S. Nemat-Nasser have been collaborating to develop an implicit algorithm for viscoplasticity in ADENA.
- Dr. Jack Stiglich of Ultramet, S. Nemat-Nasser, and J. Isaacs have been collaborating on dynamic response of tungsten.
- Collaborative work with associates from the Aeroballistic Range Association (ARA) to include participation by the Center's engineers; J. Isaacs and D. Lischer. The 41st ARA meeting, held in San Diego, included a tour of the Center's High Strain Rate Facilities and discussion of experimental techniques. Collaborative work focused on dynamic response of advanced metals.
- Collaborative work with scientists, Drs. J. Carleone, J. Muller, and R. Mundekis, from Aerojet Electronic Systems Division, on dynamic deformation and failure modes of a number of tantalum-tungsten alloys and related materials; S. Nemat-Nasser and J. Isaacs.

#### 4. FACILITIES

The Center's experimental facilities are described in the Appendix.

#### 5. EDUCATIONAL CONTRIBUTIONS

##### 5.1. Materials Program

In addition to the regular graduate studies and research in the mechanics of materials, solids, structures, and related disciplines, faculty members of the Center have initiated a full complement of undergraduate and graduate research and instruction in advanced materials. This includes: (1) Several undergraduate courses in materials science in the Department of Applied Mechanics and Engineering Sciences, and (2) A complete Masters and Ph.D. program in materials science with a set of new courses covering a broad range of important areas in advanced materials.

##### 5.2. Short Courses

The Center initiated a series of three short courses especially designed to address the training needs of scientists and engineers working in the field of dynamic behavior of materials. These courses had one-

week duration, and each focused on a specific area of interest. Instructors of the short courses were members of the University of California, San Diego/Center faculty and/or special invited guest lecturers. The emphasis of the courses was on fundamentals. Qualitative descriptions of physical phenomena were followed by mathematical derivations that established the important involved parameters. The courses were offered free-of-charge to qualified scientists or engineers from Army and other DoD laboratories and were also available to selected outside participants at an appropriate fee.

#### 5.2.1. Level of Courses

A basic knowledge of mathematics and the fundamental laws of physics, at the level of B.S. in engineering or physics, was sufficient. When more advanced mathematical procedures were involved, necessary details were provided.

#### 5.2.2. Exercises and Laboratory Sessions

The courses emphasized a "hands-on" approach. Problems were worked out in class by the instructor. They were followed by assigned problems and class discussions.

Laboratory sessions using the Hopkinson bars and gas guns were developed. These sessions were not just *demonstrations*. Students were involved in planning and pre-test calculations, performing the experiments, and the analysis of the resulting data.

Characterization of the dynamically deformed materials was performed in the laboratories of the Center under the supervision of the instructors.

The computational segment of the course was carried out with the active participation of students, starting with elementary problems with a one-dimensional code (MY1DL) running on a personal computer and progressing toward two- and three-dimensional codes (PRONTO, DYNA-2D and DYNA-3D) that ran on the CRAY supercomputer.

#### 5.2.3. Lecturers

The faculty, engineers, and graduate students of the Center are and were highly qualified to teach such a sequence of courses. The areas of expertise of the principal instructors are described below.

- S. Nemat-Nasser, Director, CEAM: Micromechanics; constitutive modeling; advanced computational methods.
- M.A. Meyers, Associate Director, CEAM: Materials effects at high strain rates, shock-material interactions.
- H. Murakami, Associate Professor of Materials Science, UCSD: Composite materials, finite-element applications.
- D.J. Benson, Assistant Professor of Applied Mechanics and Engineering Sciences, UCSD: Computational solid mechanics, large scale computations.
- G. Ravichandran, Assistant Professor of Materials: Dynamic deformation and fracture; experimental and diagnostic methods.
- K.S. Vecchio, Assistant Professor of Materials: Characterization of materials by advanced techniques.
- L.W. Meyer, Senior Scientist, Fraunhofer Institute of Applied Materials Research, West Germany: Material behavior under uniaxial and biaxial dynamic loading.
- J.B. Isaacs, Development Engineer: Experimental techniques, instrumentation, and data acquisition.
- B. Altman, Center Graduate Student Fellow: Experimental mechanics and material science.

Additionally, the Center collaborated with scientists at national laboratories whose expertise contributed to some of the courses.

#### 5.2.4. Timetable and Outline of Courses

The courses had a duration of five days and each was taught primarily by two instructors. The course consisted of in-class lectures in the mornings, followed by laboratory or problem-solving sessions in the afternoons. Typically, each course had a total of twenty hours of lectures and fifteen hours of laboratory/problem-solving. A tentative sequence of courses with a proposed schedule, the primary topics covered, and the proposed instructors are shown in Table 5. A detailed outline of course I (Dynamic Behavior of Materials) is given in Table 6, course II (Dynamic Behavior of Materials) is given in Table 7 and course III (Experimental Techniques in Dynamic Behavior of Materials) is given in Table 8.

**TABLE 5**

#### SHORT COURSES

MAR 1989	Course I: M.A. Meyers G. Ravichandran	DYNAMIC BEHAVIOR OF MATERIALS Broad Introductory coverage of the field; detailed outline follows.
FEB 1990	Course II: J.B. Isaacs L.W. Meyer M.A. Meyers S. Nemat-Nasser G. Ravichandran J. Starrett	DYNAMIC BEHAVIOR OF MATERIALS
AUG 1990	Course III: B. Altman J.B. Isaacs L.W. Meyer M.A. Meyers S. Nemat-Nasser G. Ravichandran K.S. Vecchio	EXPERIMENTAL TECHNIQUES IN DYNAMIC BEHAVIOR OF MATERIALS

TABLE 6

## COURSE I: DYNAMIC BEHAVIOR OF MATERIALS

March 6 - 10, 1989

<i>Class</i>	<i>Subject</i>
1	Structure of course; Waves, vibrating string
2	Elastic waves in continuum: Longitudinal and shear waves
3	Plastic waves
4	Plastic waves: The Taylor test
5	Hopkinson Bars
6	Plate impact experiments
7	Shock waves: Rankine-Hugoniot relations
8	Equations of state
9	Mie-Gruneisen equation of state
10	Shock and residual temperatures
11	Differential form of conservation equations
12	Finite difference analysis
13	Hydrocodes
14	Reflection and interactions, spalling, phase transformations
15	Impact: the Gurney equation
16	Detonation: Introduction, Chapman-Jouguet and equations of state
17	Explosive-metal interactions
18	Explosively accelerated devices, gas and propellant guns, electromagnetic and other techniques.
19	Measurement techniques: piezo-electric and piezo-resistive gages
20	Measurement techniques: interferometry

*List of Participants in Course I: Dynamic Behavior of Materials*

- Mr. Kent Anderson (Air Force Weapons Laboratory)
- Dr. Steven G. Barnhart (Sandia National Laboratories)
- Lt. John H. Beatty U.S. (Army Materials Technology Lab)
- Major Steven Boyce (Air Force Office of Scientific Research)
- Dr. Dan Carroll (Dow Chemical)
- Dr. James B. Clark Naval (Surface Warfare Center)
- Dr. J. S. Cory (Cory Laboratories)
- Mr. Gary Coubrough (U.S. Army ARDEC)
- Mr. James F. Emslie (State University of New York)
- Dr. John Gill (Air Force Weapons Laboratory)
- Dr. Steven M. Harris (Sandia National Laboratories)
- Mr. Richard Harrison (Ballistic Research Lab)
- Mr. Renner B. Hofmann (Air Force Weapons Laboratory)

- Mr. Timothy H. Kaiser (Science Applications Intl., MS #12)
- Capt. Timothy Kreitinger (Air Force Weapons Laboratory)
- Dr. Antoine Lahoud (Universite de Sherbrooke)
- Mr. Allen J. Lindfors (Naval Weapons Center)
- Mr. Larry M. Moore (Sandia National Laboratories)
- Dr. Hilton Murphy (S-Cubed)
- Dr. Jungjo Pyun (FMC Corporation)
- Mr. Juvenal Q. Salomon (Air Force Weapons Laboratory)
- Mr. Brent Satterthwaite (Air Force Weapons Lab)
- Mr. Craig Wittman (Honeywell Defense and Underseas Systems)

TABLE 7

## COURSE II: DYNAMIC BEHAVIOR OF MATERIALS

February 12 - 16, 1990

<i>Class</i>	<i>Subject</i>
1	Elastic waves and Hopkinson Bar
2	Plastic waves
3	Hopkinson compression, torsion and tension bars; Problem solving and calculations
4	Taylor test
5	Shock waves and plane impact
6	Shock waves: Equations of state, shock and residual temperatures
7	High speed photography of Taylor Test
8	Differential form of conservation equations: Finite difference analysis, artificial viscosity, hydrocodes
9	Shock waves; spalling, attenuation, and phase transformations
10	Numerical Analysis: Computations using MY1DL code; Demonstration of calculations on CRAY
11	Material behavior at high strain rates; Constitutive equations
12	Shear bands
13	Dynamics fracture
14	Impact experiment in large gas gun; spalling experiment
15	Experimental techniques to study dynamic deformation; equipment
16	Measurement techniques for dynamic deformation; diagnostics
17	Tour of laboratories and observation of spalled specimen on scanning electron microscope, laser interferometry, laser impulse apparatus demonstration, flash x-ray, gasless combustion synthesis

*List of Participants in Course II: Dynamic Behavior of Materials*

- Dr. James A. Ang (Sandia National Labs)
- Mr. Hugh M. Denny (USA Ballistic Research Lab)
- Dr. Milan K. Dutta (USA SDC (DOD))
- Dr. Eliot Fang (Sandia National Labs)
- Mr. Richard A. Grayson (USA Ballistic Research Lab)
- John Hawkins (Calspan Corporation)
- Mr. Donald E. Hoke (Sandia National Labs)
- Paula Jackson (Kirtland Air Force Base)
- Ltc. Thomas M. Kiehne (DARPA/TTO)
- Mr. W. Proffer (S-Cubed)
- Mr. Robert Roybald (Department of the Air Force)
- Dr. Stewart Silling (Sandia National Labs)
- Michael R. Sivack (U.S. Army Ballistic Research Lab)
- Mr. Bill Walsh (Battelle Memorial Institute)
- Mr. Darin Wilkins (S-Cubed)
- Dr. Kwanho Yang (Central Research Advanced Ceramics Laboratory)

**TABLE 8**

**COURSE III: EXPERIMENTAL TECHNIQUES  
IN DYNAMIC BEHAVIOR OF MATERIALS**

August 6 - 10, 1990

*Class      Subject*

*Lectures*

- |    |   |
|----|---|
| 1  | Elastic waves and Hopkinson Bar   |
| 2  | Plastic waves   |
| 3  | The Taylor Test   |
| 4  | Shock waves; equations-of-state, shock and residual temperatures          |
| 5  | Detonation: Chapman-Jouguet equation-of-state                             |
| 6  | Shock waves; spalling, attenuation, and phase transformations             |
| 7  | Material behavior at high strain rates                                    |
| 8  | Experimental techniques to study dynamic deformation                      |
| 9  | Characterization methods for dynamically deformed and fractured materials |
| 10 | Measurement techniques for dynamic deformation                            |

*Laboratory Sessions*

- |   |  |
|---|--|
| 1 | Hopkinson bars (compression, tension, and torsion) |
| 2 | High-speed photography of Taylor Test              |

- 3 Numerical Analysis; computations using MY1DL code and demonstrations of calculations on CRAY
- 4 Impact experiment in large gas gun; spalling experiment
- 5 Characterization of damaged metals, ceramics and composites by optical, scanning, and transmission electron microscopy

*List of Participants in Course III: Experimental Techniques in Dynamics Behavior of Materials*

- Lt. Rodman Abbott (U.S. Navy)
- Mr. Bizhan Aref (U.S. Air Force)
- Mr. Roderic C. Don (USA Ballistics Research Lab)
- Mr. Bill Merten (EG & G Mound Applied Technologies)
- Mr. Patrick Schleitweiler (EG & G Mound Applied Technologies)
- Mr. S. Stadler (NA)
- Dr. Nobuo Takeda (RCAST, The University of Tokyo)
- Mr. John N. Thomas (U.S. Air Force)

### 5.3. Focused Lecture Series and Workshops

The Center sponsored workshops and/or focused lecture series on specific topics of interest in advanced materials, especially for high strain rate applications. A focused lecture series on *Instrumentation and Measurement at High Strain Rates* was held on March 23 and 24, 1988, and proved to be successful, judging from the reaction of the participants. It consisted of a two-day, in-depth lecture series on instrumentation and measurement at high strain rates. The lecture series was followed by a one-day workshop on *Dynamic Response of Materials*. Although it was our intent to limit the total participation, including people from the University of California, San Diego, to no more than 50, the focused lecture series and workshops were attended by a total of 80 people from various national laboratories, industry, other universities, and the University of California, San Diego.

*Participants from Army and National Laboratories*

- A. Chang, Materials Testing Laboratory
- L. Burton, Ballistics Research Laboratory
- M. Hankin, Materials Testing Laboratory
- R. Kaste, Ballistics Research Laboratory
- P. Vincent, Materials Testing Laboratory
- D. Lassila, Lawrence Livermore National Laboratory

*Contributing Participants from National Laboratories*

- J. Asay, Sandia National Laboratories
- P. Follansbee, Los Alamos National Laboratory
- C. Frantz, Los Alamos National Laboratory

- W. Herrmann, Sandia National Laboratories
- R. McQueen, Los Alamos National Laboratories

#### 5.4. Workshops and Joint Conference

• Workshop on *Dynamic Response of Materials* was sponsored by the Center at the University of California, San Diego, September 28 and 29, 1989. Three areas were covered: (1) dynamic synthesis and processing; (2) dynamic flow and fracture; and (3) dynamic probing. The intent was to coordinate and develop closer contact between scientists at UC-based national laboratories (LLNL, LBNL, SNL, and LANL) and researchers at Caltech, UC Irvine, and the University of California, San Diego.

##### *Participants from National Laboratories*

- M. Boslough, Sandia National Laboratories
- J. Gilman, Lawrence Berkeley National Laboratories
- D. Grady, Sandia National Laboratories
- R. Graham, Sandia National Laboratories
- G. Gray, Sandia National Laboratories
- W. Nellis, Lawrence Berkeley National Laboratories

##### *Participants from Caltech and UCI*

- T. Ahrens (Caltech)
- W. Knauss (Caltech)
- A. Rosakis (Caltech)
- E. Lavernia (UCI)

• Workshop on *Penetration Mechanics*; the Ballistic Research Laboratory Conference was sponsored by the Center at the University of California, San Diego, was held on June 26, 1990. Three objectives were covered: (1) to coordinate collaborative work among UCSD, Ballistic Research Laboratory and Materials Testing Laboratory scientists; (2) to focus on basic problems of interest to army laboratories; and (3) to plan future exchange and collaboration.

##### *Participants from Ballistic Research Laboratory (BRL) Conference*

- Dr. William Bruchey (U.S. Army Ballistic Research Lab)
- Dr. Shun-Chin Chou (Army Materials Technology Lab)
- Dr. Dennis E. Grady (Sandia National Laboratories)
- Dr. G. Hauver (U.S. Army Ballistic Research Lab)
- Dr. Kailasam R. Iyer (U.S. Army Research Office)
- Dr. Lee Magness (U.S. Army Ballistic Research Lab)
- Mr. M. Raftenberg (U.S. Army Ballistic Research Lab)

- Dr. Steve Segletes (U.S. Army Ballistic Research Lab)
- Dr. John W. Walter (U.S. Army Ballistic Research Lab)
- Mr. T.W. Wright (U.S. Army Ballistic Research Lab)
- Dr. Richard Chait (U.S. Army Material Command)

*Agenda for the Ballistic Research Laboratory Conference*

- Introduction
- Experiments with Ceramics - G. Hauver
- DU & WHA Penetrators - L. Magness
- Computation for Ceramics - S. Segletes
- Hole Growth Computations - M. Raftenberg
- Laboratory Tour and Discussion

• Explomet '90 - International Conference on Shock-Wave and High-Strain-Rate Phenomena in Materials, was sponsored by the Center at UCSD on August 12-17, 1990. Attended by 200 participants from various universities and Army Laboratories, EXPLOMET '90 provided a forum for the exchange of information on the material effects and applications of shock-waves and high-strain-rate phenomena. One of the conference objectives was the acceleration of progress in the field of high-strain-rate deformation and fabrication.

• International Symposium on Micro-Mechanics: Homogenization, Heterogenization, and Strength, jointly sponsored by the Center at UCSD, March 27-29, 1991. Attended by approximately 85 participants to honor the 70th birthday of George Herrmann and his influence worldwide on individuals and institutions alike, in teaching and research in Applied Mechanics.

• The Society of Engineering Science held its 29th Annual Technical Meeting at UCSD, jointly sponsored by the Center. The conference brought together approximately 200 scientists and engineers to discuss a wide variety of topics in the broad field of engineering science and mechanics. A special symposium on Shear Instabilities and Viscoplasticity Theories was coordinated and chaired by Drs. M. Meyers, L. Anand, T.W. Wright, K. Iyer, Y. Bai, R.C. Batra, M. Scheidler, S.C. Chou, and R.W. Armstrong.

### 5.5. Seminar Series

The Center sponsored, either independently or jointly with other interested departments, seminars on topics of current interest. A list of seminars sponsored during the last four years is given below. (The seminars which were jointly sponsored with other institutes within UCSD are appropriately designated.)

October 1, 1986, K. Hayashi, Institute of High Speed Mechanics, Tohoku University: In-situ Tectonic Stress Determination by Hydraulic Fracturing: A New Method Employing an Artificial Notch\*

October 27, 1986, M. Taya, University of Washington, Seattle: Mechanical Behavior of Metal-Matrix

\* Co-sponsored with the Department of Applied Mechanics and Engineering Sciences, University of California, San Diego

## Composites in Severe Environments\*

November 3, 1986, D.P. Flanagan, Sandia National Lab: Computational Methods for Cratering and Material Erosion\*

November 24, 1986, M.A. Meyers, New Mexico Institute of Mining and Technology: Stress-Wave Induced Martensitic Transformation\*

January 12, 1987, D. Srolovitz, Sandia Labs: Impurity Effects in Grain Growth: Theory and Simulation\*

March 13, 1987, M.J. Salkind, Director Aerospace Sciences, Air Force Office of Scientific Research: The Changing Perception of Science and Engineering in Our Society

March 16, 1987, T. Belytschko, Northwestern University: Computational Methods for Penetration and Impact Problems\*

April 6, 1987, W. Herrmann, Sandia Labs: Shock Response of Solids\*

April 14, 1987, M. Hori, J. Starrett, AMES Dept UCSD: Void Collapse and Void Growth in Crystalline Solids J. Starrett: Discussion of New Ideas for Multiaxial Dynamic Testing Instruments\*\*\*

April 20, 1987, D. Krajcinovic, University of Illinois at Chicago: Micromechanically-Based Damage Theories\*

April 27, 1987, S. Suresh, Brown University: Crack Growth in Ceramics under Cyclic Compression: Theory, Experiments and Applications\*

April 28, 1987, M. Natori, Institute of Space and Astro-nautical Science, Japan: Space Structures - An Overview\*\*

May 11, 1987, B. Lawn, National Bureau of Standards: Toughness of Ceramics: Origins and Implications\*

May 12, 1987, A. Marchand, Brown University: Review of Dynamic Experimental Studies of Materials at Brown University\*\*\*

May 26, 1987, A. Hoger, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Conjugate Measure of Stress and Strain\*\*\*

June 15, 1987, S. Chang, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Martensitic Transformation Induced by Tensile Stress Pulse in Fe-22.5%Ni-4%Mn Alloy\*\*\*

June 22, 1987, D. Chung, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: A New Development in Phenomenological Modelling of Rate-dependent Plasticity for FEM Solution of Ultrahigh Strain Rate Problems\*\*\*

July 6, 1987, M. Staker, Army Materials Technology Lab: Necessary and Sufficient Conditions for Adiabatic Shear Band Formation in 4340 Steel\*\*\*

July 9, 1987, H. Horii, University of Tokyo: Fracture Process Zone Model in Fracture of Ceramics, Concrete and Rocks\*\*\*

July 10, 1987, R. Arrowood, Jr., University of California, Irvine: Compression Fracture of a 85% Alumina Ceramic

\*\* Co-sponsored with California Space Institute and Scripps Institution of Oceanography

\*\*\* Informal Discussion Meeting

July 16, 1987, J. Christoffersen, Technical University of Denmark: A Class of Initially Isotropic Elastic Materials\*\*\*

July 17, 1987, G. Olson, Massachusetts Institute of Technology: Displacive Transformations in Materials Science and Engineering

July 21, 1987, S. Nemat-Nasser, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Toughening by Partial or Full Bridging of Cracks in Ceramics and Fiber Reinforced Composites\*\*\*

July 28, 1987, T.W. Wright, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland: On Adiabatic Shear Bands\*\*\*

August 18, 1987, G.K. Haritos, Air Force Office of Scientific Research: Heterogeneous Damage Mechanics - Future Challenges\*

September 18, 1987, J. McKittrick, Massachusetts Institute of Technology: Rapid Solidification of Oxide Materials:  $ZrO_2$  ceramics, Y-Ba-Cu-O Superconductors\*

October 19, 1987, R.D. Caligiuri, Failure Analysis Associates: Microstructure on Properties of Alloys at Ultrahigh Strain Rates

November 18, 1987, K.T. Ramesh, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: A Plate-impact Experiment and Computational Modeling of the Rheology of Certain Amorphous Materials\*

November 23, 1987, Danny Halverson, Lawrence Livermore National Laboratories: Processing and Characterization of  $B_4C/Al$  Composites

November 25, 1987, D. Benson, University of California, San Diego, Department of Applied Mechanics and Engineering Sciences: An Overview of Explicit Finite Element Methods

November 30, 1987, Ilhan Aksay, University of Washington: Processing-Property Relation in Ceramic-Matrix Composites

January 22, 1988, Marc A. Meyers, New Mexico Institute of Mining and Technology: Novel Thermochemical-Shock Processing Methods for Powders\*

January 25, 1988, George Herrmann, Stanford University: The Dual Mechanics in Physical and Material Space with Applications to Fracture\*

February 9, 1988, Keith Kedward, Alcoa Defense Systems, Inc: The Impact of Anisotropy in Advanced Composite Structures\*

February 12, 1988, Michael J. Salkind, Air Force Office of Scientific Research: Promoting University - Industry Ties

March 3 and 4, 1988, X. Markenscoff, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Dislocation Dynamics and Elastic Precursor Decay\*

March 10, 1988, Naresh N. Thadhani, New Mexico Institute of Mining and Technology: Shock Compaction of Superhard Materials

March 17, 1988, John R. Willis, University of Bath: Overall Behavior of Nonlinearly Viscous Composites\*

April 4, 1988, Alan Zehnder, California Institute of Technology: Experiments in Dynamic and Elastic-Plastic Fracture Mechanics\*

April 5 and 7, 1988, S. Nemat-Nasser, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: The Application of Internal State Variables to Description of

## Nonlinear Material Response\*

April 19, 1988, Junji Tani, Institute of High Speed Mechanics, Tohoku University: Quenching of Superconducting Magnets Due to Mechanical Disturbances\*

May 2, 1988, Adnan H. Nayfeh, University of Cincinnati: Interaction of Ultrasonic Waves with Multilayered Anisotropic Media\*

May 23, 1988, Robert A. Jurf, Alcoa Defense Systems: Failure Analysis of Bolted Joints in Composite Laminates\*

June 6, 1988, Massoud Simnad, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Processing High  $T_c$  Ductile Superconductors\*

July 8, 1988, J.-Y. Chang, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Latent Hardening in Copper Single Crystal\*

July 21, 1988, M.A. Zikry, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Crystal Plasticity

July 22, 1988, Tarek Shawki, Department of Theoretical and Applied Mechanics, University of Illinois, Urbana-Champaign: On the Analysis of Pre-Initiation and Post-Initiation Regime for Shearband Formation in Thermal Viscoplastic Solids

July 29, 1988, Francis Rose, Aeronautical Research Laboratory, Australian Defense Department: Mechanics and Micromechanics of Reinforcement

August 4, 1988, Wolfgang Sachse, Department of Theoretical and Applied Mechanics, Cornell University: What's New in Quantitative Ultrasonics?

August 8, 1988, Baha El-Aidi, California Institute of Technology, Pasadena: Nonlinear Dynamic Analysis of Concrete Gravity Dams

September 8, 1988, Lee M. Taylor, Sandia National Laboratory: Computational Aspects of Three-Dimensional Impact Dynamics

October 10, 1988, Ronald Bullough, United Kingdom Atomic Energy Authority: Stress-Driven Impurities Segregation to Cracks and Grain-Boundaries\*

October 24, 1988, Kenneth S. Vecchio, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: In-situ Fatigue study of Al-Li-X Alloys\*

November 21, 1988, Don Shockey, SRI International, Menlo Park, CA: Frasta - A New Fractographic Technique with Uses in Failure Analysis and Materials Development\*

December 5, 1988, Aleksander J. Pyzik, Dow Chemical Company, Midland, Michigan: Processing, Chemistry and Properties of  $B_4C$ -AL Composites\*

December 19, 1988, Lee Tanner, Lawrence Livermore National Laboratory: Pre-Transformation Effects in Ni-AL System\*

January 30, 1989, S. Nemat-Nasser, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Compression-Induced Ductile Flow of Brittle Materials and Brittle Fracturing of Ductile Materials\*

February 13, 1989, Helmut Kirchner, University of Paris, Orsay: Stress Intensities at Wedges, Cracks, and Interfaces\*

February 16, 1989, Mark Rashid, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: A Constitutive Algorithm for Rate-Dependent Crystal Plasticity

February 23, 1989, S. Nemat-Nasser, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Asymptotic Solution of a Class of Strongly Singular Integral Equations

February 27, 1989, John Dundurs, Department of Civil Engineering and Mechanical Engineering, Northwestern University: Cavities Vis-a-Vis Rigid Inclusions and Other Cute Results in Elasticity\*

March 2, 1989, Muneo Hori, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Periodic Structures in Micromechanics

April 6-14, 1989, John Willis, University of Bath, United Kingdom: Lectures on Dynamic Fracture and Composites (Series of 4 lectures)

April 24, 1989, James R. Rice, Visiting Scholar at California Institute of Technology from Harvard University: Crack Tip Elastic-Plastic Fields in Ductile Crystals

April 25, 1989, A.D. Romig, Sandia National Laboratories: X-Ray Microanalysis in the Analytical Electron Microscope: Applications to the Study of Phase Stability and Diffusional Kinetics

April 26, 1989, Zafar Iqbal, Corporate Technology Laboratories, Allied Signal Corporation: The BI- and TL- Based High Temperature Superconductors: Synthesis, Superconducting Properties and Microstructure\*

May 8, 1989, David M. Barnett, Department of Materials Science and Engineering, Stanford University: Waves in Anisotropic Linear Elastic Solids

May 9, 1989, Dennis Viechnicki, Ceramics Research Branch, Army Materials Technology Laboratory: Ceramics for High Energy Impact Applications

May 12, 1989, Subrata Mukherjee, Department of Theoretical and Applied Mechanics, Cornell University: Sensitivity Analysis of Solid Mechanics Problems by the Boundary Element Method

May 22, 1989, Ronald J. Dimelfi, Independent Consultant in Materials Science, San Diego: The Thermodynamics of Thermally-Activated Micro-Mechanical Events and Its Relation to Macroscopic Mechanical Behavior

June 5, 1989, Joseph Kestin, Distinguished Visiting Professor, University of Delaware: Compatibility of the Hypothesis of Local Equilibrium with the Clausius-Duhem Inequality

June 12, 1989, K.K. Chawla, New Mexico Institute of Mining and Technology: Interface Engineering in Ceramic Matrix Composites

June 21, 1989, A.K. Zurek, Materials and Technology Division, Los Alamos National Laboratory: Fracture Behavior of Spalled 4340 and 1008 Steels

July 25, 1989, G. Ravichandran, Department of Applied Mechanics and Engineering Sciences/CEAM, University of California, San Diego: Dynamic Fracture: Theory and Applications

August 11, 1989, A.B. Sawaoka, Tokyo Institute of Technology, Japan: Shock Consolidation of Diamond Powder

August 18, 1989, A.A. Deribas and V. Nesterenko, Special Design Office for High Rate Hydrodynamics, Novosibirsk, USSR: Shock Processing of Materials in the USSR

August 25, 1989, J.R. Klepaczko, University of Metz, France: Dynamic Crack Initiation at Different Loading Rates: Experimental Methods and Modeling

August 31, 1989, M.A. Ahmadshahi, Department of Applied Mechanics and Engineering Sciences/CEAM, University of California, San Diego: Computer Based Techniques for Holographic Fringe Pattern Information Detection

September 7, 1989, T. Sekine, National Institute for Research in Inorganic Materials, Tsukuba, Japan: Shock Synthesis of Diamond

September 15, 1989, K.A. Johnson, Centers for Materials Science Los Alamos National Laboratory, Los Alamos, New Mexico: Dynamic Compaction Effects on High Temperature Superconducting  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$

October 30, 1989, L.W. Meyer, Inst. für Angewandte Materialforschung, Bremen, Germany, Visiting Scholar, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Strength Deformability and Failure of Swaged Metallic Composites Under Quasistatic and Dynamic Loading

November 2, 1989, S. Ghatuparthi, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Measurement of Interface Strength by Laser Pulse Induced Spallation

November 6, 1989, R.P. Ingel, US Naval Research Laboratory: Physical Microstructural and Thermomechanical Properties of Zirconia Single Crystals

November 20, 1989, S. Nemat-Nasser, Department of Applied Mechanics and Engineering Sciences/CEAM, University of California, San Diego: Thermal Fracturing

December 4, 1989, Robert Ritchie, Department of Materials Science and Mineral Engineering, University of California Berkeley: Mechanisms of Subcritical Crack Growth in Engineering Metals, Ceramics and Composites\*\*\*\*

January 8, 1990, George Johnson, Department of Mechanical Engineering, University of California, Berkeley: Macroscopic Anisotropy as a Result of Texture\*\*\*\*

January 22, 1990, Ali Argon, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge: Creep Resistance of a Nickel-Based Superalloy\*\*\*\*

January 29, 1990, John W. Hutchinson, Department of Mechanical Engineering, University of California, Santa Barbara: Crack Paths in Brittle Adhesive Layers\*\*\*\*

February 5, 1990, Ilhan A. Aksay, Department of Material Science Engineering, University of Washington, Seattle: Biomimetic Processing of Ceramics and Ceramic-Metal Composites\*\*\*\*

February 26, 1990, Michael M. Carroll, School of Engineering, Rice University: Mechanics of Porous Materials\*\*\*\*

March 5, 1990, George J. Dvorak, Department of Civil Engineering, Rensselaer Polytechnic Institute: Some Exact Results in Micromechanics of Fibrous Media\*\*\*\*

March 12, 1990, Anthony G. Evans, Department of Engineering Materials, University of California, Santa Barbara: Advanced Materials: New Frontiers\*

March 14, 1990, Gary G. Tibbetts, General Motors Research Laboratories: Vapor-Grown Carbon Fibers: Production, Properties, and Applications (Special Seminar)

April 2, 1990, John R. Willis, University of Bath, England: Bounds for the Properties of Nonlinear Composites: Recent Results\*\*\*\*

April 15, 1990, John R. Willis, University of Bath, England: Inclusions in Constrained Anisotropic Media (Informal Seminar)

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\*\*\*\* Co-sponsored with Materials Science Program, University of California, San Diego

April 20, 1990, Vijay Gupta, Dartmouth College, Hanover, New Hampshire: Problems in Interface Fracture (Informal Seminar)

April 23, 1990, George T. (Rusty) Gray, III, Materials Science and Technology Division, Los Alamos National Laboratory: Influence of High- Strain Rate and Shock-Loading Deformation on the Structure / Property Response of Ni<sub>3</sub>Al, Ti<sub>3</sub>Al, and TiAl\*\*\*\*

April 30, 1990, Douglas J. Bammann, Applied Mechanics Department, Sandia National Laboratories: Modelling the Large Deformation and Failure of Metals\*\*\*\*

May 7, 1990, Leon M. Keer, Department of Civil Engineering, Northwestern University, IL: The Elastic Quarter Space under Arbitrarily Applied Surface Loading\*\*\*\*

May 10, 1990, G. T. (Rusty) Gray, III, Materials Science and Technology Division, Los Alamos National Laboratory, New Mexico: "Soft" Shock Recovery Studies: Motivation and Experimental Design (Informal Seminar)

May 14, 1990, Rich Balanson, IBM: Technical Challenges in the Data Storage Industry - The Drive Toward one Gigabit per Square Inch\*\*\*\*

June 4, 1990, U. Fred Kocks, Los Alamos National Laboratory, New Mexico: Living with Anisotropic Plasticity\*\*\*\*

June 7, 1990, G. T. (Rusty) Gray, III, Materials Science and Technology Division, Los Alamos National Laboratory, New Mexico: Effects of Shock Deformation on Titanium (Informal Seminar)

August 28, 1990, Sridhar Krishnaswamy: Measurement of Transient Crack-Tip Deformation Fields (Informal Seminar)

September 6, 1990, Akira Chiba, Department of Materials Science and Resource Engineering, Kumamoto University, Japan: Underwater Shock consolidation of Difficult-to-Consolidate Powders\*

October 8, 1990, Hidenori Murakami, Department of Applied Mechanics and Engineering Sciences: Micromechanical Modeling and Finite Element Analysis of Composite Materials\*\*\*\*

October 15, 1990, R.Z. Valdiev, Institute of Metals Superplasticity Problems, USSR Academy of Sciences: Structure and Superplasticity of Al-Base Submicron Grained Alloys\*

October 22, 1990, John B. Kosmatka, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: The Use of Composite Materials in Aerospace Structures\*\*\*\*

October 29, 1990, Michael J. Sailor, Department of Chemistry, University of California, San Diego: Properties and Applications of Soluble Conducting Polymers\*\*\*\*

October 31, 1990, David Worledge, Electric Power Research Institute, Palo Alto, CA: Technical Status of "Cold Fusion"† \*\*\*\*

November 5, 1990, T. Don Tilley, Department of Chemistry, University of California, San Diego: Precursors Transition Metal Silicates Based on Tris(t-butoxy) Siloxide Complexes\*\*\*\*

November 21, 1990, Sia Nemat-Nasser, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Variational Methods in Elasticity\*\*\*\*

November 26, 1990, Joanna McKittrick, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Synthesis and Processing of Ceramic Materials\*\*\*\*

January 28, 1991, W. Edward Olmstead, Northwestern University: Asymptotic Analysis of Adiabatic

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† Co-sponsored with Center for Energy and Combustion Research/Chemical Engineering Department, University of California, San Diego

#### Shearbanding\*\*\*\*

February 4, 1991, Enrique J. Lavernia, Department of Mechanical Engineering, University of California, Irvine: Solidification Behavior of Al-Li-SiC<sub>p</sub> Materials using Variable Co-Deposition of Multi-Phase Materials\*\*\*\*

February 11, 1991, Massoud Simnad, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego: Materials Science and Technology in the Space Enterprise\*\*\*\*

February 25, 1991, Andreas M. Glaeser, Department of Materials Science and Mineral Engineering, University of California, Berkeley: Microdesigned Interfaces: New Opportunities for Materials Science\*\*\*\*

#### 5.6. Special Lecture Series

- Special Lecture Series by Dr. Paul Follansbee of Los Alamos National Laboratory on "Constitutive Modeling for High Strain Rates"
  - April 14, 1988, Deformation Kinetics at Constant Structure
  - April 26, 1988, Thermally Activated Deformation
  - April 28, 1988, Structure Evolution
  - May 3, 1988, Modeling Deformation Kinetics
  - May 5, 1988, Experimental Observations
- Special Lecture Series by Professor John R. Willis of the University of Bath on "Dynamic Fracture" and "Composites."
  - April 6, 1989, Dynamic Fracture: Theoretical Foundations
  - April 7, 1989, Dynamic Fracture: Solutions and Applications
  - April 11, 1989, Composites: Theory and Homogenization
  - April 13, 1989, Composites: Applications to Problem Solving
- Special Lecture Series by Professor G. Ravichandran of the University of California, San Diego on "Stress Waves in Solids."
  - October 6, 1988, Uniaxial Stress Waves
  - October 13, 1988, Plane Waves, Hugoniot Elastic Limit
  - October 20, 1988, Reflection and Refraction, Waveguides
  - October 27, 1988, Split Hopkinson Bar
  - November 3, 1988, Plate Impact Experiments
  - November 10, 1988, Plastic Waves, Shock Waves, Dynamic Fracture

#### 5.7. Visits by Center Personnel to Army, DoE Laboratories and Other Institutions

- Dr. John E. Starrett of the URI Center visited some of the dynamic testing facilities at Los Alamos National Laboratory on July 8, 1986, and discussed with Dr. Paul Follansbee and Mr. Charles Frantz experimental facilities which were being planned at that time for the Center.
- Dr. John E. Starrett of the URI Center visited Stanford Research Institute and Lawrence Livermore National Laboratory on July 9, 1986, reviewing some of the existing dynamic testing facilities.
- Professor S. Nemat-Nasser, Dr. John E. Starrett and Mr. Jon Isaacs of the URI Center visited the Army's MTL in Watertown, Massachusetts; the Armament Research and Development Center, Picatinny Arsenal, Dover, New Jersey; and the Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, between December 7 and 11, 1987.

They met with the directors and a number of scientists at these Army Laboratories; briefed the interested scientists there of the objectives, research plans, and other relevant activities of the Army's URI at the University of California, San Diego; and discussed in small, private discussions many scientific issues of mutual interest which could gainfully be pursued for future exchange and collaboration.

- Professor S. Nemat-Nasser visited the University of Dayton Research Institute of Impact Physics Laboratory, Dayton, Ohio, on May, 11, 1988, and reviewed with the Director and Institute scientists research plans and other activities of the URI Center at the University of California, San Diego.
- Professor Marc A. Meyers and graduate student Jerry LaSalvia of the URI Center visited BRL on December 16 through 18, 1988, and discussed with a number of scientists their work on self-propagating high-temperature synthesis of ceramics.
- Dr. John E. Starrett and Mr. Jon Isaacs visited Dr. William Nellis' laboratory at Lawrence Livermore National Laboratory on May 31, 1989, to review the two-step gas gun facilities that are used for shock compaction and shock processing of advanced materials.
- Mr. M. Zikry, graduate student and ARO's fellow, visited BRL June 19-29, 1989.
- Professor S. Nemat-Nasser visited Sandia National Laboratories for a Workshop on Continuum Damage June 11-13, 1990.
- Professor S. Nemat-Nasser visited Japan in September 1990. He presented a Keynote Speech on "New Frontiers in Dynamics Recovery Testing of Advanced Composites: Tailoring Microstructure for Optimal Performance," which was presented at the JSME Semi-Annual Meeting at Tohoku University, Sendai. Upon his visit to Tohoku University, Sendai, he presented a seminar on "Paradoxes, Facts and Fiction in Material Failure Under Compression." At the University of Tokyo, a seminar was presented on "Experimental, Theoretical, and Computational Research in Dynamic Deformation of Advanced Materials: Recent Trends." Upon his visit to Niigata, he presented a special lecture, as part of the JSCE Annual Meeting, on "Strain Localization in Granular Flow." His trip was completed by a visit to Kyushu University, Fukuoka, where he presented a lecture on "Paradoxes, Facts and Fiction Under Compression."
- Professor S. Nemat-Nasser visited the Naval Research Laboratory in February 1991, to serve as a member of the External Core Review Panel to review the Task Area: Materials and Structural Mechanics.
- Professor S. Nemat-Nasser visited the Army Material Technology Laboratory in February 1991. He presented a lecture on "Recovery Experiments and Computational Plasticity: Two Recent Breakthroughs."
- Dr. Mark M. Rashid and Professor Nemat-Nasser visited the Ballistic Research Laboratory (BRL) to coordinate the UCSD-BRL/MTL collaboration with Drs. John Frasier, John Walter, Bruce Burns, Tony Chou, and Kailasom Iyer in February 1991. Professor Nemat-Nasser presented a seminar "Experimental, Theoretical, and Computational Research in Dynamic Deformation of Advanced Materials: Recent Trends." He also visited the Army Materials Testing Laboratory (MLT) to coordinate UCSD-MTL collaboration, and to present a seminar on the same subject as above.

## 6. RESEARCH EFFORTS

In a *recovery* experiment, a sample is subjected to a well-defined load or deformation history, and then recovered for post-test microstructural characterization. Together with a complete pre-test analysis of the material's microstructure, this provides for a basic understanding of the relation

between the material's microstructure and its mechanical or thermomechanical performance. Through advanced synthesis and processing techniques, one may then seek to control the microstructure for optimal performance.

The basic understanding of the micromechanics of damage evolution associated with loading histories, is then translated into, preferably simple, microthermomechanical models which capture the essential features of the involved mechanisms. Based on these models, constitutive relations are developed and implemented into computer codes by means of suitable algorithms, and used to predict flow, failure, and general performance of structural elements consisting of advanced materials, as well as the resulting complete structure. These computer codes, with robust computational algorithms of physically-based constitutive relations, provide powerful tools for engineering design and performance evaluation of advanced structural systems.

Therefore, our research efforts at UCSD (ARO/URI) spanned the entire spectrum of the Center's main objectives, namely:

- full material characterization;
- coordinated recovery experiments over a broad range of strain rates, from quasi-static to strain rates exceeding  $10^6/s$ , with complete time-resolved measurements;
- physically-based micromechanical modeling;
- micromechanically-based phenomenological models;
- computational constitutive algorithms; and
- simulations, validation, and model verification.

With such a research program we were able to systematically study the nonlinear response and failure modes of metals, metal-matrix composites, ceramics, and ceramic composites, based on fundamental understanding of the involved physics.

The response and failure modes of ceramics and ceramic composites are dramatically different than those of metals and metal-matrix composites. Therefore, we have addressed fundamental issues pertaining to the general classes of *brittle* and *ductile* materials in their own right. For the first class (i.e., *brittle* materials), for example, the strain to failure is usually very small (e.g., less than 2%), and the inelastic response and failure modes involve damage initiation and evolution by microcracking and crack growth and coalescence. For ductile metals (e.g., copper, steel, titanium and aluminum), on the other hand, considerable plastic and viscoplastic deformation may precede and accompany various modes of microdefect generation and evolution. The strains to failure for this class of materials are generally considerably larger than those for ceramics and ceramic composites. Although the distinction between *brittle* and *ductile* materials may, at times, be unclear, it provides a useful classification, at least in certain ranges of temperatures and strain rates. (Note that ceramics can be superplastic at elevated temperatures, for low strain rates, and many metals become brittle at low temperatures and high strain rates.)

The experimental facilities developed at the University of California, San Diego include many innovations which, for the first time, provide opportunities to *perform full recovery experiments on brittle as well as ductile materials*. These facilities are briefly discussed in Section 6.5. and are also outlined in the Appendix. In addition, there are several papers in Section 7 of this report, which describe the facilities and the experimental techniques; see the publications marked with an asterisk (\*) and the following report:

"Hopkinson Techniques for Dynamic Recovery Experiments," S. Nemat-Nasser, J.B. Isaacs and J.E. Starrett, *Proceedings of the Royal Society of London, A*, Vol. 435 (1991), 371-391.

In the sequel, theoretical and computational research efforts which have been carried out under this URI, are described in a broad sense. Research topics are listed in Section 6.5.

### 6.1. Modeling and Computation: Ductile Materials

The aim of our research in this area has been to develop physically-based constitutive models for high strain high strain rate deformation of a broad class of ductile materials, and to implement these constitutive relations into computer codes through novel and efficient algorithms. Our work has focused on general viscoplasticity, addressing the strain, strain rate, and temperature, and their history effects on the constitutive response and failure modes. In particular, we have made excellent progress in the following specific areas:

- Within a general framework which includes both rate-dependent and rate-independent material response, we have formulated phenomenological models for the high strain high strain rate deformation of crystalline solids and granular (work in progress) materials, including rate and temperature effects, and strain rate history and frictional effects. These models are being tested on several materials such as copper, aluminum, certain titanium alloys, tungsten, and several steels. Parallel with this work, we are producing experimental data at various strain rates, for future implementation in the models.
- Micromechanically-based modeling of slip-induced rate-dependent plastic flow of crystalline solids, including the strain rate history, the temperature, and other effects.
- Novel (true breakthroughs) constitutive algorithms for efficient and very accurate solution of a broad class of visco-plastic and elasto-plastic materials.
- Modeling of adiabatic shear bands in terms of first-order discontinuities. This is a novel idea which treats adiabatic shear bands as discontinuities which evolve in time, according to their thermomechanical constitutive relations. We are now formulating these constitutive relations.

Considerable progress has been made in all areas, and some important results have been obtained. In particular, algorithms have been developed which, in conjunction with the large-scale computer programs PRONTO and DYNA, can routinely produce unstable deformations by localization. This is an important development, since up to now it has not been possible to produce such observed results without recourse to specialized programs and techniques.

Another area which has received both theoretical and experimental attention at the Center is ductile failure by void growth or void collapse. In particular, it has been demonstrated that void collapse and void growth in ductile materials are essentially distinct and different processes. A more interesting result, which was first demonstrated theoretically and later verified experimentally, is that very ductile fcc crystalline solids, such as copper, can actually fail by brittle-type tensile fracturing if deformed in *compression*. It is well known that the class of materials of this kind cannot usually undergo brittle-type fracturing if subjected to tension. Under tension, a crack will quickly blunt, and ductile fracture by void growth ahead of the crack tip will result. Under pure compression, however, the material can actually undergo cleavage cracking normal to the direction of compression. A theory has been developed to explain this. A systematic experimental program is currently underway. In particular, the following materials have been, and continue to be, the subject of extensive theoretical modeling at our Center: Single-crystal and polycrystal copper; 1018 and 4340 Steel; and Armco pure iron.

### 6.2. Modeling and Computation: Brittle Materials

Dynamic deformation and failure modes of ceramics and ceramic composites have become subjects of considerable interest. There are, however, many difficult issues relating to experimental techniques, characterization, and modeling of this class of materials, that require careful study, before quantitative constitutive models with reliable predictive capability are proposed. (Many existing models are based on classical ideas relevant to metals and, therefore,

are of limited value.)

At UCSD we have made a number of important contributions which specifically address the response and failure modes of ceramics and ceramic composites. A series of novel experimental techniques are discussed in Section 6.5. Here we examine the theoretical work.

### 6.3. General Comments on Response of Ceramics to Impact Loading

When a projectile impacts brittle ceramics, stress waves are imparted to the ceramic. At high enough stress wave amplitudes, compression waves can generate tensile cracks which grow dynamically, essentially parallel to the direction of maximum compression. In the neighborhood of the impactor, microcracks are initiated which interact and coalesce, resulting in eventual fragmentation and pulverization of the ceramic. Therefore, in general, under suitably large impact velocities, one may distinguish a region of pulverized ceramic undergoing granular flow in the neighborhood of the projectile, leading to another neighborhood of fragmented ceramic, leading to fractured regions and finally, possibly to intact material. The process may be accompanied by phase transformation and other inelastic phenomena in certain appropriate cases.

The theoretical research at UCSD sought to understand and model this phenomenon at various relevant stages, as follows:

- Initial dynamic tensile cracking and its influence on material stiffness and stress pulse attenuation.
- Micromechanical modeling of densely-spaced interacting microcracks, using a periodically distributed idealization. Crack coalescence and fragmentation was modeled, and the influence on stiffness degradation was rigorously quantified.
- Flow of pulverized ceramics was modeled, by considering frictional sliding accompanied by dilatancy. A constitutive model was hence developed, based on a double sliding model which included pressure effects, frictional effects, and coupling between shearing and volumetric strain.

The experimental and theoretical work addressed the following materials:

- Ceramic composites with partially stabilized zirconia
- Silicon nitride
- Alumina
- Boron carbide aluminum
- Titanium carbide and titanium diboride (e.g. produced by SHS technique at UCSD and BRL)
- Nicalon-aluminum phosphide

### 6.4. Other Fundamental Theoretical Work on Ceramics and Ceramic Composites

In the course of our research on brittle materials, a number of basic problems have emerged. The solution to some of these problems have resulted in the development of several general techniques with broad applicability.

- *Crack bridging and singular perturbation of a class of strongly singular integral equations:* A mechanism of toughening in ceramics and ceramic composites is crack bridging by ligaments or fibers. Addressing this problem mathematically, we have developed a general framework for systematically solving a broad class of strongly singular integral equations. This class of mathematical problems also emerges in other physical situations. Hence, our

novel contribution has stimulated additional work in the applied mathematics community. Our work in this area has been extensively referenced, although it has been published only recently.

- *Interface cracks in anisotropic materials:* Interface cracks develop in bimetals at various levels, including intergranular fracturing. We have considered interface cracks among general anisotropic ceramic crystal and have produced general analytic solutions for a single crack, as well as for two or more cracks which may interact with each other.

## 6.5. Experimental Research: Dynamic Recovery Experiments

A key element in our research program was the ability to perform *recovery experiments*. While quasi-static recovery tests are of common use, dynamic experiments of the same nature had remained, until quite recently, an extremely difficult task to perform, because of the difficulty in: (1) controlling the imposed loading process, and (2) obtaining reliable time-resolved data, especially for hard brittle materials such as ceramics and their composites. Fortunately, during the past few years, through a series of innovations in dynamic testing, several novel recovery testing techniques have been developed and perfected at the Center of Excellence for Advanced Materials (CEAM), at the University of California, San Diego (UCSD). This provided new opportunities for systematic evaluation of materials' microstructural evolution in a course of dynamic loading, and hence the design of microstructure for optimal performance. In this section some of these key inventions are summarized and their potential effects on the future of dynamic testing techniques are briefly discussed.

### 6.5.1. Compression Experiment

The split Hopkinson bar dynamic compression testing technique was invented by Kolsky in 1949, following the pioneering work of John and Bertram Hopkinson and R.M. Davies. In this approach, the dynamic stress-strain relation in uniaxial compression of a material is obtained by sandwiching a small sample between two elastic bars of common cross-sectional area and elasticity, called the *incident* bar and the *transmission* bar, respectively. An elastic stress pulse is imparted into the incident bar by striking it with a striker bar of given cross-sectional area and elasticity. By ensuring that all three bars remain elastic, plastic deformation is induced in the (usually) ductile sample. The stress in the sample is obtained by measuring the transmitted pulse, and the strain of the sample is calculated from the pulse reflecting off the sample, back into the incident bar, where it is measured by means of a strain gauge attached to this bar.

This classical Hopkinson (or Kolsky) bar technique is *not* suitable for recovery tests, since the reflected pulse in the incident bar is again and again reflected back into this bar, subjecting the sample to repeated compression loads. To remedy this major stumbling block in recovery experiments with the split Hopkinson (or the Kolsky) bar, a novel fixture has been developed at UCSD's CEAM, which generates in the incident bar a *compression pulse followed by a tension pulse*. In addition, *all subsequent reflected pulses which travel back toward the specimen, are tensile*. In this manner, once the tensile pulse, which tails the compression, reaches the interface between the sample and the incident bar, the sample is softly recovered, having been subjected to a known compressive pulse. As is discussed below, the shape and amplitude of this compressive pulse can be controlled, and hence the sample can be subjected to a pre-assigned stress history in this experiment.

UCSD's loading fixture for the *stress reversal Hopkinson bar* consists of an incident bar with a *transfer flange* at its loading end, and an *incident tube* resting at the one end against the transfer

flange, and at the other end, against a *reaction mass*. The incident bar, the incident tube, and the striker are of the same material (maraging steel) and cross-sectional area, i.e., they have a common impedance. The striker and the incident tube have the same length. When the striker bar impacts the transfer flange of the incident bar, the same axial compression is generated in the incident bar, incident tube, and the striker. The pulse in the incident bar travels toward the sample at the longitudinal elastic wave velocity,  $C_0$ , whereas the compression in the incident tube reflects back as *compression*, once it reaches the interface with the reaction mass. This compression travels back and loads the incident bar in *tension*, through the transfer flange. This tensile loading takes place at exactly the instant when the release tensile pulse, which has been reflected off the free end of the striker, reaches the interface with the transfer flange. The striker and the transfer flange begin to move at a third of the impact velocity opposite the impact direction, for a short time, until the striker separates from the transfer flange, bouncing back at a third of its initial impact speed.

### 6.5.2. Pulse Shaping

If the length of the sample is denoted by  $l$ , then it is easy to show that the strain rate in the sample is given by  $\dot{\epsilon} = -2 \frac{C_0}{l} \epsilon_r$ , where  $\epsilon_r$  is the strain reflected off the sample into the incident bar. A *constant* strain rate is attained by imparting a *rectangular pulse* to the incident bar.

For application to very hard brittle materials such as ceramics and their composites which undergo very small strains before failing, it is often desirable to apply stress pulses with a gentle rise, in order to allow more gradual stressing of the sample. Since the response of ceramics before failing is essentially elastic, the strain rate in the sample can be made to be constant. A complete record of the stress and strain in the sample, as functions of time, is then obtained. This is related to the corresponding damage evolution in the sample through post-test sample characterization.

At UCSD, pulse shaping was attained by placing a suitable material cushion between the striker and the transfer flange, attached to the latter. A detailed analysis of the plastic deformation of this kind of cushion has been given by Nemat-Nasser *et al.* (1991) [48]. Depending on the size of the cushion relative to the bars, and the velocity and the length of the striker, different pulse shapes can be generated.

An important point to bear in mind, in relation to dynamic testing of very hard and brittle samples, is that *the sample tends to indent the bars*, and, therefore, the reflected strain in the incident bar,  $\epsilon_r$ , is *not* a measure of the strain rate in the sample. At UCSD, we attach strain gauges to the sample and directly measure the axial as well as the lateral strains of the sample as functions of time.

### 6.5.3. Tension Experiment

The classical tension split Hopkinson bar has been used to obtain stress-strain relations of samples in uniaxial stress, to *failure*; UCSD's novel technique allows for recovery experiments by trapping the compression pulse which reflects off the sample. The loading fixture consists of a tubular striker riding on the incident bar which passes through a gas gun and terminates with a transfer flange at one end and the sample at the other end. A precision gap separates the transfer flange from a *momentum trap* bar. This gap is set such that when the striker has imparted to the incident bar the entire tensile pulse, the gap is closed. Upon reflection as compression off the sample interface, this reflected pulse is then transmitted into the momentum trap bar and is trapped there.

In closing this section, we point out that it is also possible to perform *recovery* experiments with the sample having been subjected to a compression pulse *and* a tension pulse, using a modified version of the stress reversal Hopkinson technique. This requires redesigning the end of the transmission bar in contact with the sample such that, after the sample is subjected to compression and tensile pulses, it is pulled off the transmission bar. This apparatus then allows study of the Bauschinger effect under dynamic loading.

## 6.6. Plate-Impact Experiments

Whereas with Hopkinson bar techniques, uniaxial states of *stress* are produced in materials, normal plate-impact experiments are aimed at studying dynamic material response in uniaxial *strain* states. In addition, pressure-shear experiments are employed to subject a sample to a pressure pulse followed by a shear stress pulse. Here, we examine flyer plate experiments in strain rates ranging from  $10^2/s$  to  $10^6/s$  and slightly higher, excluding the extensive use of this technique to study material properties under extremely high pressures and loading rates, especially used to examine the equations of state and the shock response of materials.

### 6.6.1. Compression Experiment

In *normal* plate-impact experiments, an optically flat thin flyer plate impacts an optically flat and parallel specimen with a momentum trap attached to its back face. The displacement and velocity of the particles on the back face of the momentum trap are usually measured using normal displacement and velocity interferometers. When the impact velocity is small so that the flyer and momentum trap remain elastic, time-resolved measures of the stress state in the sample are obtained directly by this technique. Upon impact, compressive pulses are generated in the sample and the flyer plate. When the sample and the momentum trap have matched impedances, the compression pulse is transmitted to the momentum trap, reflecting back from its free surface as a tensile pulse. With a momentum trap of suitable thickness, the entire compression pulse can be trapped. Once the reflected tension reaches the interface with the sample, the momentum trap separates, carrying with it all the impact momentum. In this manner, the sample is recovered, having been subjected to a single compressive pulse of known duration.

The reflection of elastic waves off the free boundaries of the flyer, specimen, and the momentum trap disturbs the desired uniaxial strain state in the sample, resulting in fracturing of brittle specimens such as ceramics and their composites. To minimize the effect of wave reflection, Kumar and Clifton have suggested to use a star-shaped flyer plate, and Longy and Cagnoux have proposed to use star-shaped flyers, samples, and momentum traps. Unfortunately, however, neither technique can be effective, since a major cause of producing in-plane tensile stresses in the sample is the *mismatch between the size of the flyer (which is smaller) and that of the sample (which is bigger) in these cases*. This has been examined in great detail using two- and three-dimensional finite-element analysis, as well as direct careful experiments by Chang *et al.* These studies show that a star-shaped flyer can produce tension cracks in a ceramic specimen at impact velocities as low as 27 m/s. Based on their computational and experimental studies, these authors propose a new configuration which seems to minimize the problem of tensile cracking. This configuration consists of rectangular parts only, including both back-face and lateral momentum traps.

### 6.6.2. Tension Experiment

One can generate a tensile pulse of very short duration by providing a suitable *gap* between the momentum trap and the specimen. The duration of this pulse can be controlled by adjusting the size of the gap. After impact, the compressive wave which travels in the specimen is reflected off the free surface at the gap as tension, until the gap is closed, at which time the compressive

pulse is transmitted to the momentum trap. The short duration release pulse produced by the gap, travels back in the sample and can produce tensile stresses in the specimen, once it crosses the tail of the main compressive pulse. This tension is then reflected off the front face of the specimen as compression, and travels through the sample into the momentum trap and is recorded through interferometric measurements.

This novel technique has been used by Sano at UCSD to study the initiation and growth of martensitic transformation in an Fe - 31.8% Ni - 0.02% C alloy. With a 1.5 GPa pulse amplitude and at  $M_s + 10$  °C a temperature of martensite at various stages of initiation and growth was obtained, for the first time, by changing the gap size and hence the hydrostatic tensile stress pulse duration. Pulse durations of 80, 105, and 245 ns were used. It was found that the martensite in this system initiated at annealing twin boundaries.

### 6.6.3. Pressure-Shear Experiment

In this experiment, a thin flyer plate impacts a thin specimen attached to a momentum trap, at an angle to the optically flat and parallel faces of the specimen and the flyer. This produces compression and shearing of the sample. The rear surface of the momentum trap is monitored by normal velocity and transverse displacement interferometry. Here, again, the momentum trap and the flyer remain elastic, allowing the use of elastic wave relations to interpret the measured signals. The dynamic response of the material, including the dynamic shear stress-shear strain curve, nominal pressure, and the nominal normal and shear strain rates, can be obtained by measuring the projectile velocity and the normal and transverse particle velocities at the rear surface of the specimen. By varying the thickness of the specimen, the shear strain rate can be varied, and by varying the skew angle in the oblique impact and the impact velocity, one can vary the amount of pressure and shear imposed on the specimen. Thus one can study the pressure and strain-rate sensitivity of the chosen material.

In the recovery of the specimen in a normal impact experiment, a momentum trap is used which ensures that the specimen is subjected to a single pressure loading pulse. A new technique has been developed at UCSD's CEAM, which allows recovery of specimens that are subjected to both pressure and shear loading conditions. In pressure-shear plate impact experiments, when the flyer plate impacts the target, both longitudinal and shear waves are generated and propagate through the flyer and the target. The pressure and shear waves propagate at different velocities and thus, the arrival times at a given location are different. The new recovery technique at CEAM involves trapping both longitudinal and transverse momenta in a momentum trap which is in contact with the rear surface of the target assembly. Such a momentum plate alone would not remove both the longitudinal and the transverse momenta. An additional feature is needed in the form of a composite flyer plate. The durations of the pressure and shear pulses are given by the round-trip travel times of the longitudinal and shear waves in the flyer plate. The composite flyer plate arrangement consists of two plates of the same material with an interface that cannot sustain shear. This provides an arrangement in which the longitudinal wave that propagates faster traverses the entire flyer assembly whereas the shear wave that propagates slower traverses only the impacting plate of the flyer assembly. The longitudinal pressure wave that propagates in the target also propagates through the momentum plate and reflects from the rear surface of the momentum trap as a longitudinal tensile wave. The shear loading wave follows the pressure wave and begins propagating in the momentum plate at a later instant. The construction of the flyer is adjusted such that the tail of the shear pulse arrives at the interface of the momentum trap and the target, shortly after the arrival of the longitudinal tensile pulse which causes it to detach. Hence the entire transverse momentum is also trapped in the momentum trap and is carried away. In this manner one can recover specimens which have been subjected to known durations of pressure and shear pulses.

### 6.7. Laser-Induced Stress Pulse Technique

Laser-induced stress pulses can be generated in solids, by subjecting the solid to laser irradiation. This would burn off the face exposed to the laser beam. A different technique has been developed at UCSD by Ellis, in the mid-sixties. This method is being perfected at UCSD's CEAM, and does not require exposing the sample to direct laser irradiation. Instead, by means of laser energy, a thin film of, say, gold, is subjected to an intense short-duration laser pulse which heats up the film and generates a pressure pulse which is then transmitted to the specimen. The setup consists of a Q-switched ruby laser system and a stress cell. The stress cell consists of a layered arrangement, with the specimen sandwiched between two, say, quartz gauges. The gauges are used to measure the amplitude and duration of the stress pulse, before and after passage through the specimen. Their impedance must match that of the sample. This sandwich is confined in an assembly between a glass window and a block. A gold film is deposited on the glass window. The short intense pulse from the ruby laser irradiates the film. This produces intense heating of the film which expands and creates a nearly plane, high amplitude, compressional wave of duration of a few to several hundred nanoseconds. The signals from the incident and output gauges are recorded in high-speed wave-form digitizers. With a proper design and adequate laser energy, stress pulses as high as several GPa and higher can be achieved.

Using this technique, one is able to construct simple experiments to obtain important information concerning the incubation time for the onset of microcrack initiation, its dependence on pulse duration and the amplitude of the pulse. This technique is used at UCSD's CEAM to understand phase transformation in partially stabilized zirconia under plane strain loading conditions. The advantages of this technique include the repeatability of experimental conditions to a high degree of accuracy and the relatively short time between experiments. A better understanding of the deformations in the specimen will result by using a laser interferometer system. Flash X-ray can also be used to obtain physical evidence of microcracking and damage during the transit of the compressional pulse, and reflected tensile pulse. A gap between the sample and the momentum trap may be used to generate a short tensile pulse.

### 6.8. Material Characterization

We have also used extensive characterization techniques to study the evolution of the microstructure of advanced materials subjected to dynamic loading. These techniques included:

- Nondestructive characterization - ultrasonics
- Sophisticated state-of-the-art image processing, coupled to optical microscope
- Scanning electron microscopy with back-scattering studies
- Analytical electron microscopy - TEM
- X-ray diffraction

## 7. PUBLICATIONS AND MANUSCRIPTS

The following publications and manuscripts, submitted, in press, and published, were prepared wholly or partially under the sponsorship of the Army Research Office.

### 7.1. Published Books

1. *Micromechanics: Overall Properties of Heterogeneous Solids*, S. Nemat-Nasser and Muneo Hori, Elsevier Science Publishers, (1993), 687 pages.
2. *Dynamic Behavior of Materials*, M.A. Meyers, John Wiley Publishers, (1994), 669 pages.

### 7.2. Published Manuscripts

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3. "Some Basic Kinematical Relations for Finite Deformations of Continua," M. Mehrabadi and S. Nemat-Nasser, *Mechanics of Materials* Vol. 6 (1987), 127-138.
4. "Toughening by Partial or Full Bridging of Cracks in Ceramics and Fiber Reinforced Composites," S. Nemat-Nasser and M. Hori, *Mechanics of Materials*, Vol. 6 (1987), 245-269.
5. "Adding an ALE Capability to DYNA2D: Experiences and Conclusions," D. Benson, Proceedings of SMiRT Conference, Lausanne, Switzerland, August 17-21, Balkema (1987).
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9. "Micromechanics of Failure at High Strain Rates: Theory, Experiments, and Computations," S. Nemat-Nasser, Proceedings of the Symposium on Advances and Trends in Computational Mechanics and Fluid Dynamics, Joint Institute for Advancement of Flight Sciences, Washington, D.C., October 17-19, 1988, *Computers and Structures*, Vol. 30, No. 12 (1988), 95-104.
10. "First-Order Dynamic Eshelby Tensor," Y. Mikata and S. Nemat-Nasser, Proceedings of the Twenty-Fifth Annual Technical Meeting of the Society of Engineering Science, University of California, Berkeley, California, June 20-22, 1988.

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Please note in Section 7 that publications marked with an asterisk (\*) describe the facilities and the experimental techniques of the Center.

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13. "Effect of Microstructural Damage on Ultrasonic Velocity and Elastic Moduli of Partially Stabilized Zirconia," W.P. Rogers, J. Isaacs, and S. Nemat-Nasser, Proceedings of the *Review of Progress in Quantitative NDE*, San Diego, California, August 1-5, 1988, Vol. 8B (1989), 1827-1832.
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106. "Dynamic Bauschinger Effect," A. Thakur, S. Nemat-Nasser and K. Vecchio, *Acta Metallurgica et Materialia*, accepted. (also supported by ARO DAAL-03-92-G-0108 to UCSD).
107. "Fatigue in Silicon Nitride, Part-I Effect of Grain Boundary Phase on Dynamic Compression Fatigue in Hot-Pressed Silicon Nitride," V. Sharma, K. S. Vecchio, and S. Nemat-Nasser, *J. of American Ceramic Society*, submitted 8/94. (also supported by ARO DAAL-03-92-K-0002 to UCSD)
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113. "Micro- and Macro-Structural Damage Observations in Alumina Ceramics Under Pressure-Shear Impact Loading," A.R. Machcha and S. Nemat-Nasser, *Journal of the American Ceramic Society*, submitted 12/94. (also supported by ARO DAAL-03-92-K-0002 to UCSD)
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127. "The Role of Hydrostatic Pressure in the Cavitation Failure of a Superplastic Aluminum-Lithium Alloy," A.H. Chokshi and A.K. Mukherjee, *American Geological Union, Heard Volume*, submitted.



# APPENDIX

# UNIVERSITY OF CALIFORNIA, SAN DIEGO-CEAM FACILITIES

## Dynamic Testing Facilities

Hopkinson bars for compression, compression-tension, tension and torsion

### Gas Guns

60mm gas gun (up to 200 m/s)

56mm gas gun (up to 1000 m/s)

### Electromagnetic Facility

20-gram, 50-mm diameter flyer plates

Velocities of 150m/s with less than 1kJ input

Capacitor banks in excess of 20kJ available

Ignitron switching in excess of 100kA available

### Laser Impulse Facility

10J Q-switched ruby laser system

Laser pulses as narrow as 20ns

Stress pulse width as narrow as 100µm

Multi GPa stress levels

Short time-scale, plane-wave stress cells

### Dynapak Facility

High-velocity forging machine

10-20m/s impact velocities

3000-psi maximum driving gas pressure

## Diagnostic Facilities

### High-Speed Photographic Facility

Hadland Imacon 790

Cordin 330A

Ruby laser system

Beckman & Whitley drum camera

Redlake hycam

Cranz-Chardin photography

### Holographic Facility

Lasers and optics

Real-time computed holography

### Flash Radiography Facility

150 kV Hewlett-Packard flash x-ray

450 kV Hewlett-Packard flash x-ray

### Image Processing Facility

Imaging Technology Series 151 image processor

Werner Frei image lab

### Optical Interferometry Facility

Displacement and velocity interferometry

VISARS

### Digital Data Acquisition Facility

Lecroy 6880's

Nicolet 4094 C

Nicolet 4094 B's

Nicolet 310's

Sony/Texttronix RTD 710's

## Quasi-Static Testing Facilities

110-kip frame (Axial-torsional Testing)

20-kip frame (Axial-torsional Testing)

Large triaxial cell (Axial-torsional Testing)

Three 20-kip frames (Biaxial Testing)

Testing furnaces (High-Temperature Testing)

Creep machine (High-Temperature Testing)

Instron screw machines (Small Load Frames)

Fatigue machine (Small Load Frames)

## Material Characterization Facilities

Nikon metallographic microscope

Leco microhardness tester

Olympus binocular microscope

## Division of Engineering Electron Optics Lab

Cambridge stereoscan 360 scanning electron microscope

Phillips CM30 transmission electron microscope

Perkin Elmer differential thermal analyzer

## Phillips Analytical X-ray System

Computer-controlled diffractometer

Laue camera

Quantasorb apparatus

## Ultrasonic Sound-Velocity Measurement Facility

Matec MBS 8000 measurement system

Marconi 10kHz-1GHz signal generator

## Material Preparation Facilities

Powder facilities—glove boxes, mixers, ball mills

Presses

Tube and muffle furnaces

Dynapak facility

3 machine shops

## Electron Optics and Microanalysis Facility

Cambridge Stereoscan 360 SEM

Philips CM30 300kV TEM

## EXPERIMENTAL FACILITIES AND THEIR UNIQUE FEATURES

- I. Dynamic Testing Facilities
- II. Diagnostic Facilities
- III. Quasi-static Testing Facilities
- IV. Material Characterization Facilities
- V. Material Preparation Facilities
- VI. Specimen/Equipment Fabrication Facilities
- VII. Electron Optics and Microanalysis Facility

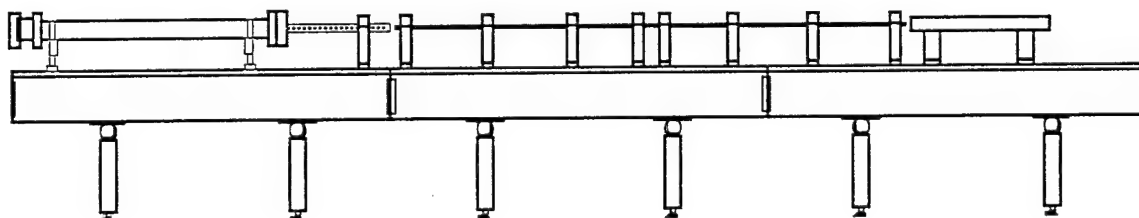
### I. Dynamic Testing Facilities

Dynamic testing facilities include Hopkinson bars, gas guns, electromagnetic loading facilities, a unique laser impulse facility and a high velocity forging facility. These instruments have been designed and chosen to provide the range of experimental capability required to support the scientific focus of the proposal.

#### *Hopkinson Bars*

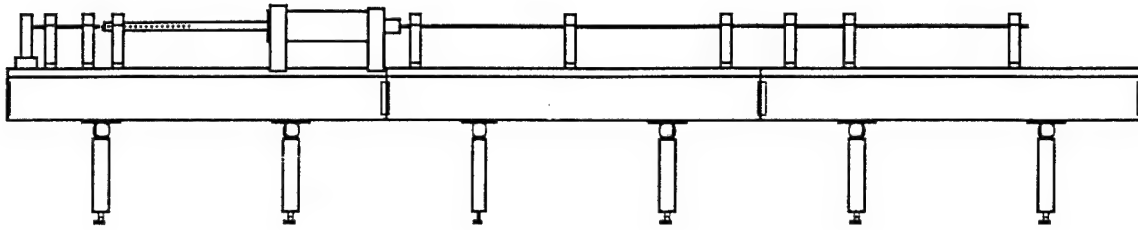
Split Hopkinson bar apparatus is used to obtain stress-strain data at high rates for materials in simple states of homogeneous stress. The flexible, modular designs include bars for Compression, Tension, Compression/Tension, Tension/Compression and Torsion testing.

#### *Compression Bar*



- Strain Rates up to 10,000/s
- Bar diameters: 3/8" to 3"
- Bar length, input and output, each: 48"
- Striker bars: 2" to 18"
- Tapered striker bars for pulse shaping
- Bar material: C350 maraging steel 350ksi yield
- Ramp pulse modification
- Stress reversal capability: Compression followed by tension; tension followed by compression (with pulse trapping)
- Momentum trapping modification for single compression, or tension, or combined pulse

### *Tension*

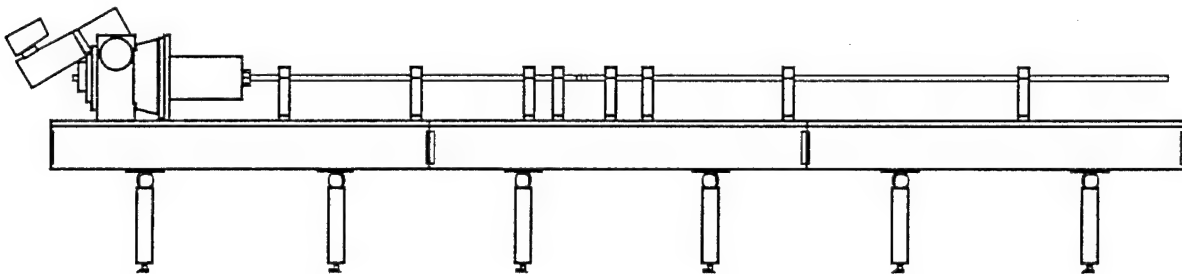


- Button end input bar gas-gun-fired annular striker design
- 3/4" bar diameter
- Maraging steel and 17-7 stainless steel bar sets
- Momentum trapping modification for single tensile pulse
- Recovery of unfailed specimens loaded by a single pulse

### *Compression-Tension*

- Installed on either compression or tension bar platforms
- Single compression pulse followed by single tension pulse
- Recovery of specimens after a single load cycle
- Recovery of specimens after a single compression pulse

### *Torsion*

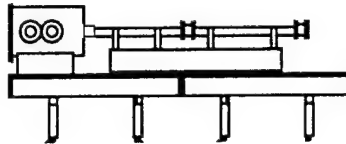


- Self-locking worm gear drive
- Precise, simple, pretorque and release mechanism
- Symmetric reaction torque
- Bending-free torsional waves
- Adaptable for multiaxial loading
- 1" diameter bar
- Variable pulse length

## Gas Guns

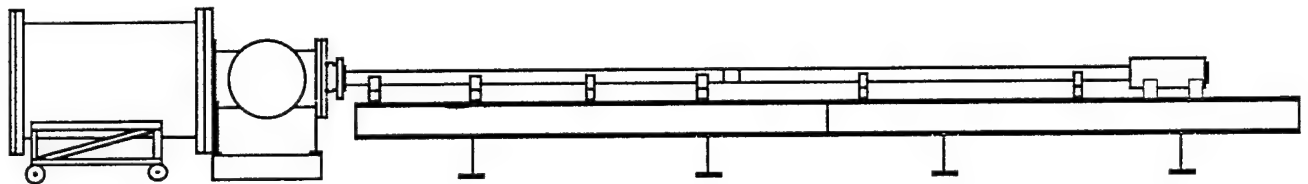
Gas guns are precision instruments for flyer plate and other impact experiments. The flyer plate experiments produce extremely high rates in exceptionally clean states of homogeneous strain. Gas guns include a small, moderate-velocity instrument of 60mm bore, and a large, high-velocity instrument of 56mm bore.

### *60mm gas gun*



- Up to 200m/s impact velocities
- Micro-grooved barrel
- Normal impact and pressure-shear experiments
- Momentum trapped recovery experiments
- Normal and transverse displacement measurements by interferometry

### *56mm gas gun*



- Over 1000m/s impact velocities
- Plate impact experiments
- Sphere and rod impact geometries
- Soft recovery system
- Complete interferometric measurement systems
- Flash X-ray radiographic capability

Note: A Ginch gas gun, particularly suited for dynamic testing of composites, is being fabricated at CEAM of UCSD. This instrument will be functional by May 1995.

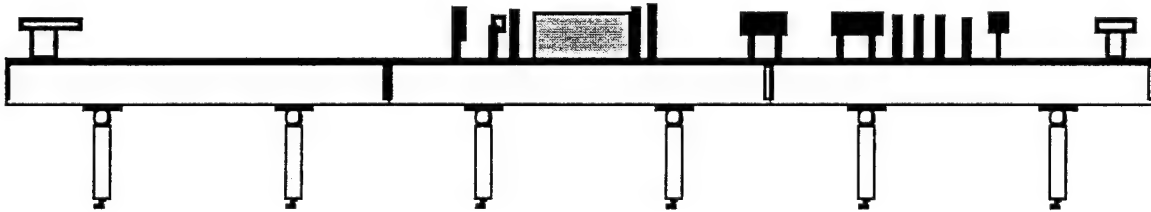
### *Electromagnetic Facility*

Electromagnetic techniques provide an alternative to mechanical methods of generating high loads and loading rates. These techniques have the special advantage of precise timing, which allow carefully coordinated loading events to produce analytically tractable states of multiaxial loading. The present apparatus is operated as an electromagnetic flyer plate launcher or for radial loading, by changing the coil and transmission line geometry.

- 20gram, 50mm diameter flyer plates
- Velocities of 150m/s with less than 1kJ input
- Fast recycling of apparatus
- Capacitor banks in excess of 20kJ available
- Ignitron switching in excess of 100kA available

### *Laser Impulse Facility*

This unique facility provides a dynamic probe for investigating phenomena such as the evolution of microcracking in brittle materials under high loading rates. Because of the precisely limited mechanical energy, specimens can be taken above failure thresholds and recovered intact for post-test characterization. The extremely short duration of the pulse makes it an ideal instrument for probing other very fast phenomena, such as stress-induced phase transformations.



- 10J Q-switched ruby laser system
- Laser pulses as narrow as 20ns
- Stress pulse width as narrow as 100 $\mu$ m (0004")
- Multi GPa stress levels
- Short time-scale, plane-wave stress cells

### *Dynapak Facility*

- High velocity forging machine
- 17,500 ft-lb energy capability
- 10-20m/s impact velocities
- 3000 PSI maximum driving gas pressure

## II. Diagnostic Facilities

Image and data acquisition capabilities include cameras up to 20 million frames per second, X-ray flash photography, computer-generated holographic interferometry, and 1.7GHz digital signal sampling.

### *High-Speed Photographic Facility*

- Hadland Imacon 790
- Cordin 330A
- Ellis Camera
- Ruby Laser System
- Megawatt Flashlamp System
- Beckman & Whitley Drum Camera
- Redlake Hycam
- Cranz-Chardin Photography

### *Holographic Facility*

- Lasers and Optics
- Real-time Computed Holography

### *Flash Radiography Facility*

- 150 KV Hewlett-Packard Flash X-Ray
- 450 KV Hewlett-Packard Flash X-Ray

### *Image Processing Facility*

- Imaging Technology Series 151 Image Processor
- Werner Frei Image Lab

### *Optical Interferometry Facility*

- Displacement Interferometry
- Velocity Interferometry
- VISARS

### *Digital Data Acquisition Facility*

- LeCroy 6880 's
- Nicolet 4094 C
- Nicolet 4094 B's
- Nicolet 310's
- Sony/Textronix RTD 710's

### III. Quasi-Static Testing Facilities

Computer controlled hydraulics and multi-axial load frames provide state-of-the-art testing of materials under quasi-static loading. The large triaxial cell facility for the study of granular materials is the only facility of its kind.

#### *Axial-Torsional Testing*

110kip Frame  
20kip Frame  
Large Triaxial Cell

#### *Biaxial and Uniaxial Testing*

Biaxial Frame  
50kip Frame  
Three 20kip Frames

#### *High Temperature Testing*

Testing Furnaces  
Creep Machine

#### *Small Load Frames*

Instron Screw Machines  
Fatigue Machine

### IV. Material Characterization Facilities

Analysis of materials is performed before and after subjection to a known loading history. Characterization study is dependent on reproducible sample preparation and analyzing equipment quality.

#### *Sample Preparation Equipment*

#### *Nikon Metallographic Microscope*

#### *Leco Microhardness Tester*

#### *Olympus Binocular Microscope*

#### *Division of Engineering Electron Optics Laboratory*

Cambridge Stereoscan 360 Scanning Electron Microscope  
Phillips CM30 Transmission Electron Microscope (see attached description)

#### *Perkin Elmer Differential Thermal Analyzer*

#### *Phillips Analytical X-Ray System*

Computer Controlled Diffractometer  
Laue Camera

#### *Quantasorb Apparatus*

*Ultrasonic Sound Velocity Measurement Facility*

MATEC MBS 8000 Measurement System  
Marconi 10kHz-1GHz Signal Generator  
Fully Computer-based with digital sampling

**V. Material Preparation Facilities**

*Powder Facilities*

Glove Boxes  
Mixers  
Ball Mills  
Presses

*Furnaces*

Tube Furnaces  
Muffle Furnaces

*Dynapak Facility*

**VI. Specimen/Equipment Fabrication Facilities**

*Materials Science Machine Shop*

*Division of Engineering Machine Shop*  
*Upper Campus Machine Shop*

**VII. Electron Optics and Microanalysis Facility**

The Division of Engineering's Electron Optics and Microanalysis Facility has two new microscopes that serve the faculty, staff, and graduate students in all of the engineering departments at UCSD, as well as some researchers from other groups on the UCSD campus. The two new microscopes are: 1) a Cambridge Stereoscan 360 scanning electron microscope with an integrated Link AN10000 X-ray analysis system, and 2) a Philips CM30 300kV transmission electron microscope also with a Link AN10000 X-ray analysis system.

The Cambridge Stereoscan 360 is a fully computer-controllable scanning electron microscope with an ultimate point-to-point resolution of 2.5nm. Coupled with the Link X-ray analysis system, qualitative, semi-quantitative, or fully-quantitative compositional analysis on the 1 micron scale is routinely available. Both secondary and backscattered electron detectors are available on the instrument, and accelerating voltages between 200 volts and 40,000 volts are selectable in step-sizes as small as 50 volts. The specimen stage can accommodate samples as large as 6" in diameter and 2" in height. However, imaging is possible only over an area 4" in diameter.

The transmission electron microscope is a Philips CM30, a high-resolution, intermediate voltage instrument with the capability of high-spatial resolution X-ray microanalysis. The instrument is fully computer-controllable, with realignment as easy as pushing a button. Accelerating voltages between 50kV and 300kV are selectable in step-sizes as small as 100 volts. The ultimate resolution of the CM30 at 300kV is 0.18nm line-to-line, and 0.23nm point-to-point. With the addition of the Link AN10000 X-ray analysis system it is

possible

to conduct high-spatial resolution (<50nm in diameter) X-ray microanalysis on elements down to beryllium on the periodic table. A wide range of specimen holders are available including: 1) a standard single-tilt holder, 2) a low background single-tilt holder for microanalysis, 3) a double-tilt low background holder for both careful diffraction work and microanalysis, 4) a liquid nitrogen low background double-tilt holder to perform the same functions as (3) except at controllable temperatures from 100°C down to -170°C, and 5) a single-tilt furnace holder capable of 1300°C. Particular expertise in the areas of bright-field, dark-field, and weak-beam imaging, as well as selected-area diffraction, convergent beam electron diffraction, high-spatial resolution X-ray microanalysis, and high-resolution imaging exists among the faculty involved with the facility.

# THE REGENTS OF THE UNIVERSITY REPORT OF INVENTIONS AND SUBCONTRACTS OF CALIFORNIA, SAN DIEGO (Pursuant to "Patent Rights" Contract Clause) (See Instructions on Reverse Side.)

Form Approved  
OMB No. 0704-0197  
Expires Jun 30, 1992

Public reporting burden for this collection of information is estimated to average 3 minutes per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0197), Washington, DC 20503.

1a. NAME OF CONTRACTOR/SUBCONTRACTOR	c. CONTRACT NUMBER	2a. NAME OF GOVERNMENT PRIME CONTRACTOR	c. CONTRACT NUMBER	3. TYPE OF REPORT (X one)
b. ADDRESS (Include ZIP Code)	d. AWARD DATE (YYMMDD)	Army	DAAL03-86-K-0169	a. INTERIM <input checked="" type="checkbox"/> b. FINAL <input type="checkbox"/>
La Jolla, CA 92093		b. ADDRESS (Include ZIP Code)	d. AWARD DATE (YYMMDD)	4. REPORTING PERIOD (YYMMDD)
			86/10/1	a. FROM 86/10/1
			86/10/1	b. TO 94/6/30

## SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR (If "None," so state)

a. NAME(S) OF INVENTOR(S) (Last, First, MI)	b. TITLE OF INVENTION(S)	c. DISCLOSURE NO., PATENT APPLICATION SERIAL NO. OR PATENT NO.	d. ELECTION TO FILE PATENT APPLICATIONS				e. CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER
			(1) United States	(2) Foreign	(a) Yes	(b) No	
	NONE		(a) Yes	(b) No	(c) Yes	(d) No	

6. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR/SUBCONTRACTOR

(1) (a) Name of Inventor (Last, First, MI)	(2) (a) Name of Inventor (Last, First, MI)
(b) Name of Employer	(b) Name of Employer
(c) Address of Employer (Include ZIP Code)	(c) Address of Employer (Include ZIP Code)

9. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED

(1) Title of Invention

(2) Foreign Countries of Patent Application

## SECTION II - SUBCONTRACTS (Containing a "Patent Rights" clause)

6. SUBCONTRACTS AWARDED BY CONTRACTOR/SUBCONTRACTOR (If "None," so state)

a. NAME OF SUBCONTRACTOR(S)	b. ADDRESS (Include ZIP Code)	c. SUBCONTRACT NO.(S)	d. DEAR "PATENT RIGHTS"		e. DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S)	f. SUBCONTRACT DATES (YYMMDD)	
			(1) Clause Number	(2) Date (YYMM)		(1) Award	(2) Estimated Completion
NONE							

## SECTION III - CERTIFICATION

7. CERTIFICATION OF REPORT BY CONTRACTOR/SUBCONTRACTOR

(Not required if Small Business or Non-Profit organization.) (X appropriate box)

a. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL (Last, First, MI)

c. I certify that the reporting party has procedures for prompt identification and timely disclosure of "Subject Inventions," that such procedures have been followed and that all "Subject Inventions" have been reported.

Bettye H. Albritton

Bettye H. Albritton  
Contract and Grant Officer

d. SIGNATURE

Dr. Nemat-Nasser

e. DATE SIGNED